Assessing the Effects of Urban Development & Climate change on Flooding in the Greater Port-Harcourt Watershed, Niger delta, Nigeria.

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DECLARATION

This thesis has been composed wholly by me, Nimi G Dan-Jumbo, and is my own original work. No part of this thesis has been submitted for any other degree or professional qualification.

Signature ……………….

Date…25-10-2017……

ABSTRACT

Developing countries have been rapidly urbanising over the last decades, resulting in major environmental pressures and increased vulnerability to natural disasters. A complex combination of factors, including climate change, land use change, poorly implemented regulation and a lack of integrated planning has often resulted in environmental degradation and disproportionate impacts of natural disasters affecting millions worldwide, particularly in tropical cities. The main aim of this study is to understand the effects of land-use and climate change on flooding in the Greater Port-Harcourt watershed. The specific research objectives were: to understand the historical and future land use /land cover changes; to understand the magnitude of change in hydrologic and hydraulic conditions due to land-use and climate changes; to assess the influence of different forest mitigation scenarios on peak-discharge; and to make recommendations on how to improve future planning using insights from this study. Methodologically, the post-classification change detection method was applied to examine the extent and nature of historical LULC changes using remotely sensed data. Future LULC changes were estimated by superimposing the 2060 digitised Masterplan map on the year 2003 baseline imagery. Hydrologic changes were assessed using HEC-HMS model, while changes in the hydraulic condition were assessed using HEC-RAS model. Model output was further used to map flood hazards, flood zones and damage potential. Priority areas and infrastructure at risk were identified by means of their location in flood zones and exposure to floods with high damage potential.

On the extent of change, this study revealed that urbanisation and loss of agricultural land had been the dominant and intensive land use change in the watershed. Urbanisation is projected to almost double its 2003 extent by 2060 and is likely to remain the dominant force of land use change. On the nature of change, this study found that urban land was the most dynamic in terms of gross gain and net change. It exhibited the grossest gain (about 9% of the watershed) and the grossest loss leading to a high net change of about 8.6%. In fact, the most prominent transition was the conversion of agricultural land (about 422km^2) to urban land, and roughly 93.3% of all conversions to urban land resulted from agricultural land. On the process of change, urban land mainly experienced a net-type of change (change in quantity), whereas changes in agricultural land was more of a swap-type of change (change in location). Importantly, the study reveals that the impact on flood flow was historically significant (about 68%) and is projected to amplify in future, however, these changes are largely attributed to increased storm size. Urbanisation is likely to have little or no impact on annual maximum peak flow at the watershed scale; however, urbanisation is projected to have a considerable impact on peak flow in a number of subbasins, which could have severe implications for flash flooding in those subbasins. Similarly, afforestation could have little or no impact on future maximum peak flow when assessed at

the watershed scale. Although some subbasins experienced changes in peak flow, the effect of forest is variable. The study concludes that although the impact of urbanisation is projected to be insignificant at the watershed scale, it could also increase flood risk due to increasing developments in floodplains and channel encroachment. Priority infrastructure and areas requiring urgent flood risk management include the Port-Harcourt seaports, Onne seaport, the University of Science and Technology and cement factory. Priority areas in the Masterplan are mainly in the south (Phase 3), comprising of the Air force base and the residential area near Onne seaport. Lastly, approximately 8.1km and 189m of road and rail network are at greater risk of flooding by means of their exposure to floods with the highest damage potential.

Based on this study, I have furthered understanding by showing that the transition to urban land category was dominated by net changes (i.e. changes in quantity). I have also furthered understanding by showing that substantial changes in future urban land-use may not have significant effect on flood parameters. My main contribution to knowledge is that despite the high rate of urbanisation in the GPH watershed and its minimal impact on flooding (which could be due the large size of the storm and watershed), urbanisation could still increase flood risk due to greater exposure of elements at risk in the flood plains to damaging floods. Based on the results, the study recommends that the development authorities should integrate both structural measures (mainly for flood defence around existing developments) and non-structural measures (primarily for future developments). For flood risk management research, this study recommends that conclusions about the effects of urbanisation should not be made solely on the basis of changes in hydrology and river hydraulics, however researchers should also consider the exposure of important elements at risk within the floodplains under study to better understand the effects of urbanisation. Moreover, to better understand urbanisation effects on runoff dynamics in other watersheds, this study recommends that research efforts should be concerted in understanding subbasin-scale changes given that the effects of urbanisation are more pronounced in smaller basins.

LAY ABSTRACT

Developing countries have been rapidly urbanising over the last decades, resulting in major environmental impacts and increased vulnerability to natural disasters. The main aim of this study is to understand the effects of land-use and climate change on flooding in the Greater Port-Harcourt watershed. Methodologically, the post-classification change detection method was applied to examine the extent and nature of historical land use changes using remotely sensed data. Future land use changes were estimated by overlaying the 2060 digitised Masterplan map on the 2003 baseline imagery. Hydrologic changes were assessed using a rainfall-runoff model, while changes in the hydraulic condition were assessed using hydraulic model. Model output was further used to map flood hazards, flood zones and damage potential of the study area. Priority areas and infrastructure at risk were identified by means of their location in flood zones and exposure to floods with high damage potential.

In terms of the extent of change, this study revealed that urbanisation and loss of agricultural land had been the dominant and intensive land use change in the watershed. Urbanisation projected to almost double its 2003 extent by 2060 is likely to remain the dominant force of land use change. On the nature of change, this study found that urban land was the most dynamic in terms of gross gain and net change. Importantly, this study reveals that the impact on maximum peak flow was historically significant (about 68%) and is projected to amplify in future, however, these changes are largely attributed to increased storm size. Urbanisation is likely to have little or no impact on maximum peak flow at the watershed scale; nevertheless, it is projected to have a considerable impact on peak flow in a number of subbasins, which could have severe implications for flash flooding in some subbasins. Similarly, afforestation could have little or no impact on future maximum peak flow when assessed at the watershed scale. The study concludes that although the impact of urbanisation is projected to be insignificant at the watershed scale, it could still increase flood risk due to increasing developments in floodplains. Priority infrastructure and areas requiring urgent flood risk management include the Port-Harcourt seaports, Onne seaport, the University of Science and Technology and cement factory. Lastly, approximately 8.1km and 189m of road and rail network are at greater risk of flooding by means of their exposure to floods with the highest damage potential. Based on this study, I have furthered understanding by showing that the transition to urban land category was dominated by net changes (i.e. changes in quantity). I have also furthered understanding by showing that substantial changes in future urban land-use may not have significant effect on flood parameters. My main contribution to knowledge is that despite the high rate of urbanisation in the GPH watershed and its minimal impact on flooding (which could be due the large size of the storm and watershed), urbanisation could still increase flood risk due to greater exposure of elements at risk in the flood plains to damaging floods.

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ABBREVIATIONS

AE	Absolute Error
AMC	Antecedent Moisture Content
AMDR	Annual Maximum Daily Rainfall
ANOVA	Analysis of Variance
AOI	Area of Interest
BE	Biological/Ecological
CBD	Central Business District
CEQ	Council on Environmental Quality
CN	Curve Number
DEAT	Department of Environmental Affairs and Tourism
DEM	Digital Elevation Model
DF	Debris Factor
DPR	Department for Petroleum Resources
EA	Environmental Assessment
EC	European Commission
EIA	Environmental Impact Assessment
EIS	Environmental impact statement
EMP	Environmental Management plan
EMS	Environmental Management System
ERML	Environmental Resource Managers Limited
ETM	Enhanced thematic mapper
FEPA	Federal Environmental Protection Act
FGN	Federal Government of Nigeria
FHA	Flood Hazard Assessment
FHM	Flood Hazard Mapping
FMEnv	Federal Ministry of the Environment
GCM	Global Climate Model
GFDRR	Global Facility for Disaster Reduction and Recovery
GMT	Greenwich Mean Time
GPH	Greater Port-Harcourt
GPHDA	Greater Port-Harcourt Development Authority

HAF	High Afforestation
HEC	Hydrologic Engineering Center
HIA	Health Impact Assessment
HMS	Hydrologic Modelling System
IFRC	International Federation of Red Cross and Red Crescent
IPCC	Intergovernmental Panel on Climate Change
IS	Impermeable Surface
LAF	Low Afforestation
LCM	Local Climate Model
LGA	Local Government Authority
LULC	Land use/Land cover
MAE	Mean Absolute Error
MDG	Millennium development goals
MLC	Maximum likelihood classifier
MRE	Mean relative Error
NDDC	Niger Delta Development Commission
NESREA	National Environmental Standards and Regulations Enforcement Agency
NF	No Forest
NIHSA	Nigeria Hydrological Services Agency
NRCS	Natural Resources Conservation Service
ODPM	Office of the Deputy Prime Minister
RAS	River Analysis System
RE	Relative Error
RMSE	Root Mean Square Error
RR	Rainfall-Runoff
SCS	Analysis of Variance
SE	Squared error
SEA	Strategic Environmental Assessment
SPDC	Shell Petroleum Development Company
SRTM	Shuttle Radar Topography Mission
SuD	Sustainable Development
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TM	Thematic Mapper

UK	United Kingdom
UMP	Urban Masterplan
UNCED	United Nations Conference on Environment and Development
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNECA	United Nations Economic Commission for Africa
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTM	Universal Traverse Mercator
UUMP	Urban Sprawl plus Urban Masterplan
WCED	World Commission on Environment and Development
WSE	Water Surface Elevation
WSP	Water Surface Profile

Chapter 1. Introduction

1.1 BACKGROUND.

Cities in developing countries are growing at an unprecedented rate, resulting in profound and unintended environmental impacts (Wheater and Evans, 2009; Jha et al., 2012; Miller et al., 2014). Increased flood risk resulting from heavy rainfall, land-use changes, channel and floodplain dwelling is putting millions of inhabitants of new mega-cities in danger (Wheater and Evans, 2009; Jha et al., 2012; Ngoran and Xue, 2015). In particular, tropical cities in developing countries are increasingly at risk of flooding due to worsening natural and anthropogenic influences (Ithnin, 1992; Halwatura and Najim, 2013; Munji *et al.*, 2013). Natural forces, including intense precipitation, high tide, and low topography demand careful management. Moreover human influences due to urbanisation that result in rapid land-use changes and increased flood risk requires better managemnet (Jha et al., 2012; Owei et al., 2010; Munji et al., 2013).

Urbanisation is broadly defined as the transition from rural to largely urban societies (Jha et al., 2012. By 2014, more than half (54%) of the world's population were living in cities (Jha et al., 2012; UN, 2014). By 2050, urban population is projected to rise by 2.5 billion people, with 90% of this population anticipated to be concentrated in Asia and Africa and 60% of this population expected to live in slums (Jha et al., 2012). There is now a wide consensus that Asia and Africa are more vulnerable to flooding effects due to increased urbanisation, climate change, poor planning, weak regulations, poor socio-economic conditions and poor adaptive capacity (UNFCCC, 2007; Osti et al., 2008; Jha et al., 2012; Li et al., 2014. Therefore, there is a crucial need to understand future patterns of urbanisation and their resulting impacts on urban watersheds in these regions.

Pluvial flooding is an urban phenomenon and is described as the overflow of water onto urban land that is usually dry, which is often initiated by intense and/or prolonged rainfall. It overwhelms the capacity of the drainage system and can be due to high proportions of impervious surfaces (Pereira, 1973; Koks et al., 2014). Whilst climate-driven precipitation is the direct driver, urban flooding is compounded by increased impervious land-cover (Beard and Chang, 1979), poor drainage systems (Raghunath, 2006), as well as reduced infiltration and storage capacity of soils (Chen et al, 2009.; Leopold, 1968; Beard and Chang, 1979; Excimap, 2007). Increased impervious surfaces result from developments, whether planned or unplanned (Suriya and Mudgal, 2012; Miller et al., 2014), as such, it is important to embed an improved understanding of the indirect drivers of flooding in urban planning, especially in rapidly growing cities in the tropics.

Floods remain the most frequent and deadliest natural disaster in history (Jha et al., 2012). In the last decade, the number of deaths caused by floods was the highest among natural disasters (IFRC, 2014). Between 2003 and 2014, the World Disaster Report accounts for 63,000 people reportedly killed; US$312, 035 billion worth of damage; and 943,464 people affected worldwide (IFRC, 2014). Moreover, within the last decade, flood disasters in Asia and Africa accounted for 50% of all flood disasters in the World (IFRC, 2014). Examples of developing countries hit by recent destructive floods since 2010 include South Africa, Sri Lanka, and the Philippines, Brazil, Vietnam, Thailand, India, Malawi, Nigeria, Pakistan, etc. (Jha et al., 2012; GFDRR, 2013; Hallegatte et al., 2015).

For instance, more than 2 million people across 19 districts of Orissa, located on India's east coast were affected by heavy flooding in 2011. More than 5,700 people were missing and presumed dead in the wake of floods in the northern province of Uttarakhand, India. In Africa, Malawi was also hit by significant flooding in January 2012. The floods affected more than 10,000 people and caused US$3 million worth of damage to households and infrastructure (Hallegatte et al., 2015). Floods are happening everywhere in the world, regardless of the development status of the country, but developing countries need more attention because of their low adaptive capacity to disasters.

This thesis focuses on urban flooding affecting Greater Port-Harcourt City (GPH) in Rivers State in the Niger Delta of Nigeria, although findings could be pertinent for other riverine cities in the Niger Delta and other countries. See location of Rivers state in Appendix 1.1. Flooding is the most frequent and life-threatening environmental hazard in the country, affecting especially coastal areas in the Niger Delta (Abam, 2001; GFDRR, 2013; Akukwe and Ogbodo, 2015). A recent example was the July 2012 flood disaster which affected 12 states around the River Niger. The event left 363 people dead; US$9.5 billion worth of damage; 5,851 injured. About four million people were displaced (GFDRR, 2013). After this event, a Post-Disaster Needs Assessment report (PDNA) showed the damages in Rivers State alone was worth US$3. 4 billion (GFDRR, 2013).

GPH is a rapidly growing city undergoing planned and unplanned expansion (Verml, 2009; Ikechukwu, 2015). With a population of about two million, studies claim flood frequency may increase in the future, due to a complex combination of causes mainly from the meteorological and hydrological condition of the area (Akukwe and Ogbodo, 2015; Elenwo and Efe, 2014; Enaruvbe and Ige-Olumide, 2014). Urban areas can be flooded by rivers, coastal floods, pluvial and groundwater floods, as well as artificial system failures, but often human factors such as urbanisation aggravate floods (Plate, 2002; Jha et al., 2012). To mitigate flood damage, and improve planning in the area, there is need for improved understanding of the spatial development patterns in the GPH area and their impacts on future hydrologic and hydraulic conditions. This thesis attempts to provide understanding and recommendations for flood risk management.

1.2 AIM AND OBJECTIVES.

The aim of this research is to understand the effects of land-use and climate change on flooding in the Greater Port-Harcourt watershed. The objectives are to:

1. To understand the historical and future land use /land cover changes (LULC).
2. To understand the magnitude of change in hydrologic and hydraulic conditions due to land-use and climate changes.
3. To assess the influence of different forest mitigation scenarios on peak-discharge
4. To make recommendations on how to improve future planning using insights from this study.

To address these objectives, the thesis will address four main research questions (RQ1-RQ4) accompanied by nine secondary research questions in Table 1.1.

Table 1.1 Showing the Primary and Secondary Research Questions in this Study.

Research questions
RQ1: What are the historical and future changes in the LULC of Greater Port-Harcourt Watershed? **(addressed in Chapter 5)** 1. What was the extent and nature of historical LULC changes? 2. What is the extent of future urban LULC changes due to the implementation of the plan by 2060? 3. What are the dominant and key driving forces of land use change in the watershed?
RQ2: What are the effects of land-use and climate changes on flooding in the GPH watershed? **(addressed in Chapter 6 and 7)** 1. What are the effects of historical and future urbanisation and climate change on runoff in the entire basin? 2. What are the relative effects of the location alternative to Phase-1 project on flooding in the GPH watershed? 3. What are the effects of the entire plan on the channel flood depth, extent and velocity? 4. Where are the priority areas and important infrastructure at risk to flooding based on exposure to flood hazard?

Research questions

RQ3: To what extent could afforestation reduce flooding in the GPH watershed? **(addressed in Chapter 6)**

1. To what extent could afforestation reduce flooding in small and large storm conditions?
2. To what extent could afforestation reduce flooding in high and low afforestation conditions?

RQ4-How can the Greater Port-Harcourt Development Authority improve future planning using new insights into flood risk? **(addressed in Chapter 8)**

1.3 RATIONAL, JUSTIFICATION AND SIGNIFICANCE OF RESEARCH.

1.3.1 Need in Hydrology/Flood Risk Research.

In hydrology, much have been discussed on the effects on flooding such as: increase in peak flow, changes in total runoff, changes in water quality and effects on hydrologic amenities (Leopold, 1968; Verbeiren et al., 2013; Sanyal et al., 2014). Much has also been discussed on the effects on sediment load, effects on infiltration or the loss rate, changes in basin lag time (Harbor, 1994; Meade, 1996; Suriya and Mudgal, 2012; Nikolaidis et al., 2013). Regarding flood risk, much has also been researched on flood hazards, flood vulnerability, flood risk management (Plate, 2002; Smith, 2013; Viglione and Rogger, 2015). Others have researched on adaptation, flood mitigation, flood perception, emergency planning, etc. (Jha et al., 2012; UNFCCC, 2007; Bola et al., 2014).

Presently, there is a growing interest in foresight and future studies relating to flood impacts (Ali et al., 2011; Du et al., 2012), flood risk and vulnerability assessment (Wheater and Evans, 2009). This will help our ability to make long-term plans and explore options for flood risk management. In a recent study by Samuels (2012:10) titled "Where next in flood risk management", emphasis was laid on long-term planning and options assessment. The study emphasised on "the urgent need to improve understanding and reduce uncertainty for estimates of decadal timescale changes to floods and their impacts". Future studies are crucial for planning and formulating long-term adaptation and mitigation strategies for vulnerable areas. One major concern to planners are the options that are likely to significantly impact on the future hydrologic functioning of basins (Leopold, 1968; Pauleit and Durham, 2000). Therefore, there is need to understand the impacts of land-use change scenarios, development alternatives as well as climate change scenarios on flooding.

1.3.2 Knowledge gap on the effects of urbanisation on urban hydrology in the Niger Delta.

In the Niger Delta today, there are gaps in knowledge regarding potential impacts of urbanisation on flooding. There is a need for future impact research relating to urbanisation, since catchment response to urbanisation varies from watershed to watershed (Leopold, 1968). However, there are recent studies on potential impacts of land-use change on flooding for several catchments in other developing countries (Chen et al., 2009; Ali et al., 2011; Du et al., 2012; Sanyal et al., 2014). For example, such studies have been carried out in Qinhuai River Basin, in China by Du et al. (2012); Thirusoolam Sub-watershed in Chennai by Suriya and Mudgal (2012); Lai Nullah Basin, Pakistan by Ali et al. (2011); Tolka River Basin in Dublin, Ireland by Verbeiren et al. (2013); Gyeongancheon watershed in Korea by Im et al. (2009). These studies showed that future urbanisation could likely have a significant impact on flooding. In contrast, no such study have investigated the future impacts on flood in the Niger Delta. Such a study could be beneficial in providing further insight into the alternatives with the least impact on flooding in a tropical watershed. The study will also provide an understanding of the future impact on this important tropical watershed. Moreover, the scope of this research will go beyond the impact on hydrology to the impact of the hydraulic condition. To date research on future flood hazard parameters such as flood depth, flood extent and fluid velocity are apparently non-existent for the Niger Delta region.

1.3.3 Knowledge gap on the effects of forest on urban hydrology in the Niger Delta.

About urban and forest effects, the hydrology of large watersheds is considered more complicated to understand than small watersheds (Feldman, 2000; Wheater and Evans, 2009). Although the impacts of urbanisation on urban hydrology has received much attention in many developed countries, studies e.g. Wheater and Evans (2009) and Feldman (2000) have demonstrated that watershed responses vary from catchment to catchment depending on the climatic and physiographic characteristics of the catchment. For example, in small basins, it is expected that flooding would decrease with increased forest cover. In large catchments, it is also expected that increasing urbanisation should increase flooding, but in many cases, the effects are even more complex in large catchments than in small basins (Leopold, 1968; Hewlett and Helvey, 1970; Cosandey et al., 2005). Similarly, forest has a greater effect on runoff in smaller basins due to interception, meanwhile in large basins, the effects of forest is also more complex to understand (Hewlett and Helvey, 1970; Hamilton et al., 1983).

Tropical mega deltas enclose some of the most significant urban, agricultural and industrial developments in the world and present one of the most challenging planning and watershed management situations giving their location (at land-water interface), diverse character and influence on hydrology (Chu *et al.*, 2010). Such areas are also home to large populated cities e.g. Dhaka in Bangladesh, Bangkok in Thailand, Hanoi in Vietnam, Warri and Greater Portharcourt in Nigeria. The GPH watershed is a large tropical watershed, hence studies show that Portharcourt area and the wider Niger Delta region are undergoing large-scale changes in land-use which present enormous challenges (Enaruvbe and Ige-Olumide, 2014) (Twumasi and Merem, 2006; Daramola and Ibem, 2010; Abbas, 2012). To the best of the author's knowledge, there is no existing research about future catchment response to afforestation, climate change and urbanisation for the Niger Delta region as a whole. However, there is a crucial need to address these knowledge gaps to provide a greater understanding of catchment response for policymaking, environmental decision-making, flood risk management, forestry and urban planning in the region. Hence, findings and lessons learnt could be useful to other large riverine basins and deltas with similar demographic, geomorphic, meteorological, physiographical and ecological setting.

1.3.4 Challenges in vulnerability research in the area.

So far, previous research attempts on flooding in the GPH watershed have been limited to historical studies which use of historical data for determining impacts and vulnerable areas. There is little or no evidence or data on future catchment responses or vulnerabilities in the area. Previous research on the GPH watershed can be grouped into two. The first are studies that identify and review causal factors and historical effects as documented in Bariweni et al. (2012); Elenwo and Efe (2014). The others focus on vulnerability of receptors to floods found in Akukwe and Ogbodo (2015). These studies provide little or no understanding of future impacts of existing or future development actions in the area. Still, on flood vulnerability, a previous study with the aid of a map was able to identify vulnerable areas in the past. Hence these studies relied on historical flood data as seen in Ologunorisa (2004) and Akukwe & Ogbodo (2015). Future climate changes and land-use change data are important inputs for analysing future impacts and vulnerable areas (Schanze, 2006; Jha et al., 2012). A major setback in mapping future vulnerabilities in such regions includes limited or unavailable model input data (Farquharson et al., 1992; Shamaoma et al., 2006; Osti et al., 2008; Jha et al., 2012; Roy and Mistri, 2013). In spite of the obstacles to flood forecasting in the area, there is need to understand future impacts of land-use and climate changes.

1.3.5 Environmental challenges in Greater Port-Harcourt.

Greater Port-Harcourt is a rapidly growing city within one of the most important and sensitive wetlands in the world (Abam, 2001). The city is the main economic capital of the Niger Delta. The inner Niger Delta, widely known as the economic hub of Nigeria's rich oil economy is at the same time the world's third largest wetland (Meade, 1996; Abam, 2001; Schuyt, 2005). Demographically, it is one of two cities in the delta confronted with high population influx resulting from economic and industrial activities in the area (NDDC, 2006; Ikechukwu, 2015). It reflects the ongoing tensions between the need for economic development and environmental protection. Despite the lack of adequate amenities and infrastructure, the city continues to attract huge rural population which fosters urbanisation. For example, with an annual population growth rate of 3.0%, the population of Port-Harcourt city has surged from an estimated 180,000 people in 1963 to about 2 million in 2016 (Demographia, 2017), and by 2020 the population of 3 million is expected to rise to about 7 million in the entire Rivers State (NDDC, 2006). Therefore, efficient and sustainable urban planning is required to help protect human and natural elements at risk in the wetland.

As a result of the rapid urbanisation in the GPH area, coupled with weak implementation of planning regulations, the pattern of development, human settlement and sub-urbanisation have been largely haphazard (Owei et al., 2010; Mmom and Fred-Nwagwu, 2013; Wizor, 2014). Haphazard, scattered, unregulated, leapfrogged, ribbon and continuous low-density form of developments are referred to as urban sprawl and are by-products of urbanisation (Ngoran and Xue, 2015). Previous studies on the area have established that urban sprawl trigger a wide range of physical and biochemical changes ultimately affecting the human and natural environment including air quality, sanitation problems, vegetation clearing, loss of biodiversity, etc. Recently, its influence on urban flooding has been re-emphasized (UNDP, 2006; Mmom and Fred-Nwagwu, 2013; Elenwo and Efe, 2014; Enaruvbe and Ige-Olumide, 2014; Akukwe and Ogbodo, 2015). Despite the emphasis, little or no research have been conducted to investigate the impacts of future impact of urbanisation on its urban hydrology.

Apart from issues of recent and future urban sprawl in the peri-urban areas, the risk flooding to flood plain and flood channel dwellers south of the city has also been discussed (Ologunorisa 2004; Chiadikobi et al., 2011; Enaruvbe and Ige-Olumide, 2014). In terms of topography, the delta is flat, low-lying and does not have well-defined flood plains, such that flooding of inter-channels takes place and waterfronts are increasingly being subjected to coastal flooding. In recent decades, there has been increasing evidence of the acceleration of sea level rise to about 2-3mm/yr in the area (IPCC, 2007, 2012, 2014). According to Munji et al. (2013), climate change and the resultant rise in sea level are expected to inundate lowlands and exacerbate coastal tidal ranges. Existing studies in the area suggest the vast majority of people living in the low-lying flood plains are vulnerable to coastal flooding (Ologunorisa 2004; Akukwe and Ogbodo, 2015).

1.3.6 Gap in practice: implementation of urban planning in GPH.

In response to these urban pressures, the Greater Port-Harcourt City Development Authority (GPHCDA) established in 2009 was charged with the responsibility to meet the growth need by facilitating the implementation of the Greater Port-Harcourt Masterplan and to build the New Greater Port-Harcourt city. This is a 50-year plan with a vision to transform the GPH area into an attractive city that is internationally recognised and a preferred destination for investors and tourists. In summary, the objective was to build a well-planned city' that could yield regional economic benefits and is sustainable (Verml, 2009; Cookey-Gam, 2010; Ikechukwu, 2015). For information, implementation of the phased plan in year 2017 is under phase-1 of the development. Initially, an environmental impact assessment (EIA) was carried out to ensure sustainability considerations accompany the Phase-1A projects ERML, 2009; Cookey-Gam, 2010). While the GPHDA seek to achieve a sustainable development, studies suggest that even well-planned developments trigger unintended impact (Pauleit and Duhme, 2000).

As stated earlier, the most concern to planners are those alternatives/options that affect the hydrologic functioning of the watershed (Leopold, 1968; Pauleit and Duhme, 2000 (Wheater and Evans, 2009), but to date research on the effects of urban land-use alternatives on flooding is rare especially in the Niger Delta area. To date, only scanty information on the environmental impact of alternatives on flooding exist in literature. One previous attempt was to understand the environmental performance of different land-cover types in an urban system and its different subunits (i.e. Housing schemes, commercial and industrial developments and services) in Munich, Germany (Pauleit and Duhme, 2000). Firstly, the study was carried out in a different context. Secondly, study of the impacts of the sub land-cover types on hydrologic parameters were only limited to runoff and percentage of impervious surface (PctImp), whereas the impact on other flood hazard parameters were not considered. Another study investigated how planning alternatives could affect critical habitats (Theobald and Hobbs, 2002). Generally, impacts on urban hydrology and flood hazards are important indicators of sustainable urban planning (Pauleit and Duhme, 2000). Therefore, there is a need to assess the impact of land-use alternatives on hydrology and flood hazard parameters which are unavailable for the GPH watershed. For example, some alternatives were considered in the environmental impact assessment (EIA) of phase-1A of the project and the most preferred alternative was chosen. The alternatives include: (1) No-Project Alternative (2) Alternative location (3) Delayed Project Alternative (4) Current Project Alternative (Verml, 2009). First, there is a need to conduct hydrologic and hydraulic analysis and flood hazard mapping on the impacts of the plan. Next, an analysis of the impacts of the comprehensive Masterplan for the watershed should be carried out and not just for an isolated sub – project (Phase-1A).

1.4 THESIS OUTLINE.

This thesis is structured into eight chapters. **Chapter 2** reviews relevant theories, regulations and concepts in this research mainly related to urban flooding; sustainable urban planning; and environmental assessment. Gaps in the literature and practice are identified. The conceptual framework for the study was developed by linking the main concepts in this study. The chapter is structured into eleven main sections including: urban hydrology, effects of urbanisation on flooding, effects of climate change on flooding, flood hazards, urbanisation, forest and urban flooding, sustainable development and planning, environmental assessment in Greater Portharcourt and the conceptual framework.

Chapter 3 describes the GPH study area and project. The goal was to describe the population, development plan and biophysical environment of the area. Key sections include: a description of the geographical setting; a description of the biophysical setting; and a description of the hydrological setting of the study area and finally the GPH development (master) plan.

Chapter 4 presents the research methodology. This chapter describes and justifies the research design, and specific methods used in meeting the research objectives. This chapter is structured into research approach, data collection. It also includes the research procedures for conducting LULC change analysis; hydrological modelling, hydraulic modelling; alternatives and scenario analysis; as well as statistical data analysis.

Chapter 5 is the first empirical chapter and presents the land-use/land-cover change analysis. The chapter is the first data analysis chapter and major sections included: introduction; materials and methods; results; discussion and conclusion. Materials and methods for achieving objectives in this chapter was structured into data acquisition, image processing, supervised classification, post-classification analysis, and change detection analysis.

Chapter 6 is the second empirical chapter and contains an analysis of the impacts of urbanisation on hydrologic parameters. The goal was to assess the impact on hydrology as a result of the development plan and climate change. Also to understand the effects of afforestation on peak runoff. Main sections include an introduction; materials and method; results; discussion; and conclusion. The materials and methods for this chapter are summarised and structured into: model description, model construction, validation.

Chapter 7 is the third empirical chapter and presents a study of the impacts of urbanisation on flood hazard parameters. The goal was to understand changes in flood depth, flood velocity and flood extent as a result of the urban development plan and climate change. Main sections include: introduction; materials and methods; result; discussion; and conclusion. Material and methods were briefly described and structured into: model description, model application (pre-processing, model-run and post-processing) as well as model validation.

Chapter 8 presents the general discussion and conclusion. The chapter synthesised the main findings and discusses the main findings of the research questions. It also discusses the limitations of this research, further research and conclusion.

Chapter 2. Literature Review.

2.1 INTRODUCTION.

There is increasing evidence that changes in patterns of extreme rainfall and urbanisation are having a growing effect on flood magnitude in the 21st Century (Nicholls, 2000; Arduino *et al.*, 2005; Metz *et al.*, 2007; IPCC, 2012). Flood risk research benefit from recent advances in the hydrology, river hydraulics, hydrologic modelling, environmental change, risk management, spatial planning and environmental assessment of floods for improving our understanding of flood impacts (Leopold, 1968; Nicholls, 2002; Plate, 2002; Cooper, 2004; Reddy, 2005; Teutschbein and eibert, 2010). However, relevant review studies suggest there are still gaps in future flood research. Parker (2000a) points to the lack of extensive research on catchments in the most vulnerable areas of the world. This chapter reviews the relevant literature with the goal of identifying gaps in existing knowledge, linking prior research, concepts, topics and themes and eventually construct a conceptual framework that links the relevant concepts in this research. The study adopts relevant concepts mainly from hydrology, risk management, environmental change and also environmental assessment. The main concepts include urban flooding, flood hazard, flood risk, exposure, urbanisation, climate change, land-use changes and alternatives.

The chapter is divided into eleven main sections. Section 2.2 explains hydrology and urban flooding. Subsequently, section 2.3 discusses the flooding phenomenon. Section 2.4 expands on the effects of non-climatic and climatic factors on flooding. Next, section 2.5 discusses flood hazards. Section 2.6 deals with forest and flooding, 2.7 expands on the concept of flood hazard. Urbanisation, sustainable land-use planning, alternatives in environmental impact assessment were briefly reviewed in section 2.8. Section 2.9 reviewed the concept of sustainable development. 2.10 briefly expanded on environmental assesment in GPH, while section 2.11 presents the conceptual framwork of the study.

2.2 HYDROLOGY AND URBAN FLOODING.

2.2.1 Hydrology.

Hydrology is a branch of earth science that deals with the occurrence, distribution and disposal of water on the earth (Bras, 1990; Raghunath, 2006). Urban hydrology is a younger, interdisciplinary science that deals with the occurrence, distribution and disposal of water and its relationship with the urban environment (Lazaro, 1990). Generally, hydrology deals with the different phases of the hydrological cycle (Raghunath, 2006) as shown in Figure 2.1. The cycle mainly involves the processes of precipitation, evaporation and evapotranspiration and runoff, where urban flooding mainly results from the latter.

Water is well known a requirement for life and a hazard to man. However, the questions remain: How much water is there? Where is the water coming from? Where is it going? How can it be controlled? When is it too little or too much? (Bras, 1990). Among the watershed management problems known in hydrology (see Table 2.1), flooding is one of the most life-threatening which demands better understanding and regulatory response.

Table 2.1 showing flooding as a one of the critical watershed management problems and possible alternatives for mitigating floods. Alternative measures include reservoir storage, levee construction, channelisation and flood plain management. (Source: Brooks, 1985).

Problem	Possible Alternative	Associated watershed management objective
Deficient water supplies	Reservoir storage and water transport	Minimise sediment delivery to reservoir site; maintain watershed vegetation cover
	Water harvesting	Develop localised collection and storage facilities
	Vegetation manipulation; evapotranspiration reduction	Convert from deep-rooted to shallow-rooted species from conifers to deciduous trees
	Cloud seeding	Maintain vegetative cover to minimise erosion
	Desalinisation of ocean water	Not applicable
	Pumping of deep groundwater and irrigation	Management of recharge areas
Flooding	Reservoir storage	Minimise sediment delivery to reservoir site; maintain watershed vegetative cover
	Construct levee, channelisation etc.	Minimise sediment delivery to reservoir site; maintain watershed vegetative cover
	Floodplain management	Zoning of lands to minimise human activities in flood-prone areas; reduce sedimentation of channels
	Revegetate disturbed and denuded areas	Plant and manage appropriate vegetation cover

Problem	Possible Alternative	Associated watershed management objective
Energy shortages	Utilise wood for fuel	Plant perpetual fast-growing tree species; maintain productivity of the sites; minimise erosion
	Develop hydroelectric power project	Minimise sediment delivery to reservoirs and river channels; sustain water yield
Food shortages	Develop agroforestry	Maintain site productivity; minimise erosion; promote species compatibility with soils and climate area
	Increase cultivation	Restructure hillslopes and other areas susceptible to erosion; utilise contour ploughing, terraces, etc.
	Increase livestock production	Develop herding-grazing systems for sustained yields and productivity
	Import food from outside watershed	Develop forest resources for pulp, wood and wildlife products, etc. to provide economic base
Erosion/Sedimentation from denuded landscapes	Erosion control structures	Maintain life structures by revegetation and management
	Contour terracing	Revegetate mulch, stabilise slopes and Institute land-use guidelines
	Revegetate	Establish protect and manage vegetative cover until site recovers.
Poor quality drinking water	Develop alternative supplies from wells and springs	Protect groundwater from contamination
	Treat waters supplies	Filter through wetlands or upland forest
Polluted streams/reduces fishery production	Control pollutants entering streams	Develop buffering strips along stream channels; maintain vegetative cover on the watershed; develop guidelines for riparian zones
	Treat wastewater	Use forest and wetlands as secondary treatment systems for wastewater

2.2.2 Historical Perspective.

The historical development of hydrology as a scientific discipline is fascinating. According to Eagleson (1970), early thinkers could not easily comprehend the three basic hydrologic principles: infiltration, evaporation as well as condensation & conservation of mass. It was only in the seventeenth century that Perrault proved that precipitation was the cause of streamflow in the Seine River in France (Bras, 1990). Afterwards, the 18th Century witnessed major advances in hydraulics and pluvial water movement led by Bernoulli, Chezy and others. Up until the1930s, hydrologic science relied on qualitative descriptions and empiricism with only a little understanding of hydrologic processes (Eagleson, 1970; Parker, 2000b).

In the 1930s, Sherman (1932) and Horton (1933) emerged with more quantitative and theoretical approaches. Sherman (1932) pioneered the concept of the unit hydrograph which is used to explain the river basin behaviour. Horton (1933) promulgated the Hortonian theory on infiltration, soil moisture accounting and runoff which are still in use today (Bras, 1990; Beven, 2004). In summary, Horton theorised that overland flow is caused by excess rainfall when water exceeds the infiltration capacity of the soil. He specifically stated that:

> *"Infiltration divides rainfall into two parts, which thereafter pursue different courses through the hydrological cycle. One part goes via overland flow and stream channels to the sea as surface runoff; the other goes initially into the soil and thence through ground-water again to the stream or else is returned to the air by evaporative processes. The soil, therefore, acts as a separating surface and various hydrologic problems are simplified by starting at the surface and pursuing the subsequent course of each part of the rainfall as so divided, separately"* (Horton, 1933: 446–447).

These process-based theories are fundamental to understanding hillslope processes and urban hydrology.

2.2.3 The Hydrological Cycle.

The hydrological cycle explains all water motion on the earth. It simplifies the complex processes of water circulation (Brooks, 1985; Lazaro, 1990). In other words, the hydrological cycle describes the circulation of water in a closed system from the ocean to the atmosphere and back to the earth, via surface or underground movement (Bras, 1990). As shown in Figure 2.1, the cycle starts when moisture evaporates from ocean waters to the atmosphere. Water vapour in the atmosphere condenses into clouds and precipitates down onto land surfaces, reaching vegetation first in the biosphere. Some of the water may be evaporated and re-enter the atmosphere or become surface or sub-surface water (Lazaro, 1990).

Importantly, surface water may cause flooding through different prevailing flow regimes or their combination (Heggen *et al.*, 1996).

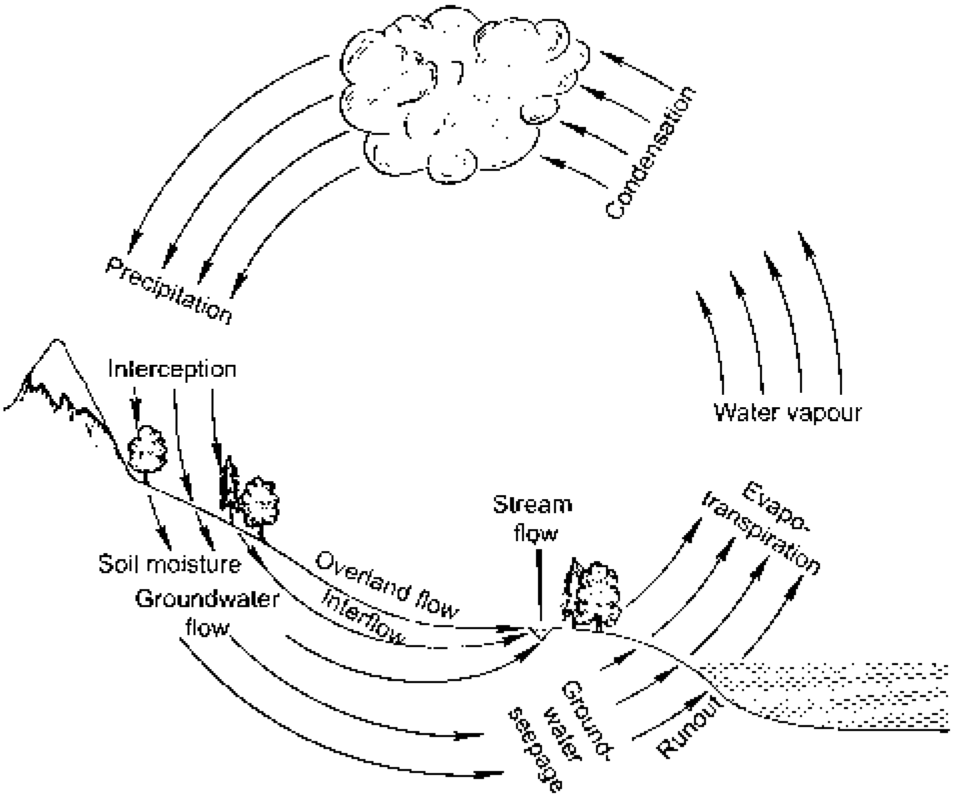


Figure 2.1 A diagram of the hydrological cycle showing the circulation of water from the ocean to the atmosphere and back to the earth via surface or underground movement (Ward, 1975).

2.2.4 Conservation of Mass Principle.

Conservation of mass and water balance allows hydrologists to quantify the changes and the amount of water in the pathway. On this principle, inputs into the hydrologic system (including rainfall, snowmelt and condensation) must be balanced with exchanges in storage and outputs (including streamflow, ground water seepage, and evapotranspiration), (Brooks, 1985; Heggen *et al.*, 1996). It implies that more inflow and less outflow equals the change in storage as seen in equation 2.1. Based on this principle, studies have indicated that the total amount of fresh water on the earth is only about 2.6%. 77% of the fresh water is tied up in glaciers and ice caps, 11% underground with only 12% of water left in circulation. It is estimated that only 0.57% of the 12% left in circulation is in the atmosphere and biosphere (Brooks, 1985; Lazaro, 1990). In hydrology, the processes of water in the biosphere often affected by human activities and vegetation are of particular interest to planners and hydrologists (Brooks, 1985; Heggen *et al.*, 1996; Feldman, 2000). Through the principle of conservation of mass, impacts and consequences of human land use change and developments can be assessed which is the focus of this research.

$$I - Q = \Delta S$$ ***Equation 2.1***

Where I=inflow, Q=outflow and ΔS = change in storage

2.3 FLOODING.

A flood can be defined as a body of water, which rises to overflow land which is not normally submerged (Ward, 1978). Floods occur due to extreme flows or when floodplains, river channels and terrains are inundated (Yevjevich, 1992). According to Heggen *et al.* (1996), floods occur when water levels in lakes, ponds, reservoirs, aquifers and estuaries exceed some critical values and inundate the adjacent land, or when the sea surges on coastal lands significantly above the sea level. A flood can also be described as a relatively high flow which overtakes the natural channel provided for the runoff (Chow, 1956). There are different types of flood including flash floods, coastal floods, urban floods, river (or fluvial) floods, ponding (or pluvial flooding) and dam floods (Merz *et al.*, 2007a). Generally, the different types of floods are linked to their origins or the nature of the area. For instance, dam floods may occur during dam failure. On the other hand, urban and coastal floods occur when urban and coastal areas are inundated. Nevertheless, urban flooding is the main focus of this research.

2.3.1 Flood and Runoff Production Mechanisms.

Until the 1960s, Sherman's (1932) theory of unit hydrograph and Horton's (1933) theory of quick flow generation primarily governed by infiltration were the widely recognised theories that explained the inland flood phenomenon. Overland flow regime was initially considered the primary flood generation mechanism (Eagleson, 1970). Today, other flow regimes such as saturation overland flow have been theorised (Heggen *et al.*, 1996; Parker, 2000a). As stated above, the Hortonian theory implied that overland flow was the prime cause of inland floodwaters and is governed by the difference between high rainfall intensity and infiltration rate (Eagleson, 1970). The theory suggests that discharge results once the rate of supply exceeds the capacity of surficial materials to absorb it; water begins to accumulate and causes overland flow down the hillslope (Heggen *et al.*, 1996). Studies suggest the Hortonian theory is mainly applicable to regions with thin soil and poorly vegetated slopes such as the arid and semi-arid regions (Jones, 2000b), suggesting that overland flow is not the main mechanism in tropical catchments.

Since the 1960s, a gamut of studies have argue against the Hortonian theory. They believe that flood waters come from more widespread sources and can be generated from a combination of different flow regimes (see Figures 2.2 and 2.3), (Betson, 1964; Hewlett and Hibbert, 1967; Kirkby and Chorley, 1967). Betson (1964) promulgated the notion of the Partial Contributing Area model, which explains the idea of Dynamic Contributing Area. The Partial Contributing Area (PCA) is a combination of throughflow (in upper hillslopes) and overland flow (in lower hillslopes). With regard to the idea of Dynamic Contributing Area, it is assumed that only a small portion (5-20%) of the catchment contributes to stream flow (Parker, 2000a).

Refinements of the PCA model eventually led to the dominance of the Variable Source Area model by Hewlett and Hibbert (1967). This model assumes that contributing areas vary from storm to storm, depending on pre-storm antecedent moisture content and distribution. Meanwhile, Kirkby and Chorley (1967) in their work advanced the idea of saturation overland flow as the main cause of quick flow. In this case, subsurface return flow and precipitation falling directly onto saturated soils are combined (see Figure 2.2 below). Despite the progress in knowledge, flood or runoff mechanisms were still not fully understood because some other mechanisms were later discovered (Jones, 1987; Parker, 2000a). For example, stormflow was also found to be generated by ground water ridging through microspores, seepage zones or naturally developed pipes termed 'pipe flow' (Figure 2.2). Generally, these processes are known as hillslope processes.

There is a wide consensus that the effects of hillslope processes are greater in small basins than in large basins (see Figures 2.3a and 2.3b), although basin response may sometimes be non-linear which contradicts the unit hydrograph theory (Jones, 2000b). According to Jones (2000b) and Heggen *et al.* (1996), the combination of flow regimes and relative dominance or any flow regime vary from storm to storm and from catchment to catchment. This indicates that catchment response is complex and cannot be generalised since it varies from place to place. This complexity suggests the need for catchment by catchment examination of the dominant flow regimes or mechanisms. It raise a question: what is the dominant flow regime in the Greater Port-Harcourt area at sub-basin scale?

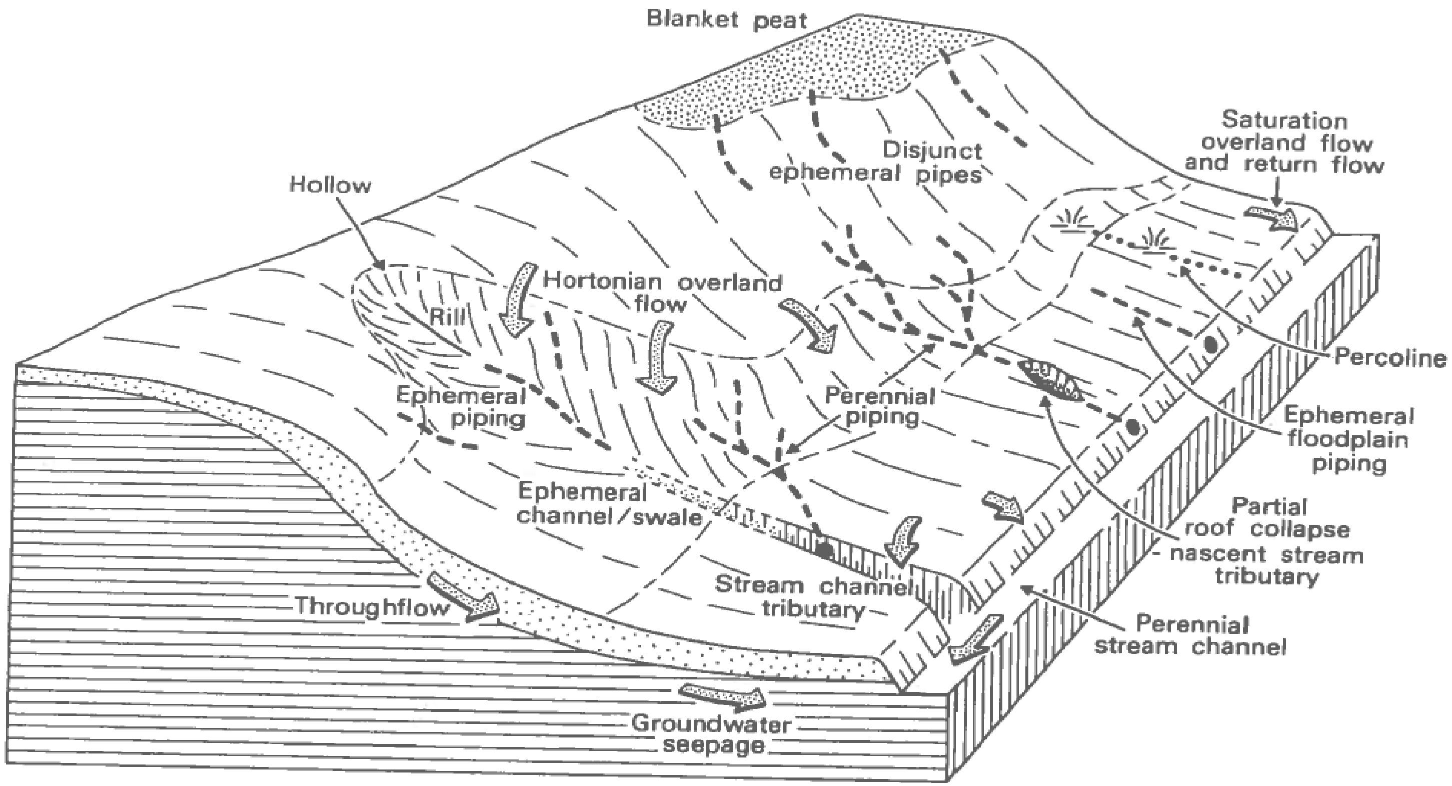


Figure 2.2 Diagram of various flow regimes and hillslope drainage routes for overland and stream flow generation. Flow regimes include Hortonian overland flow, Throughflow, Groundwater flow, Saturation overland flow (Jones, 2000a).

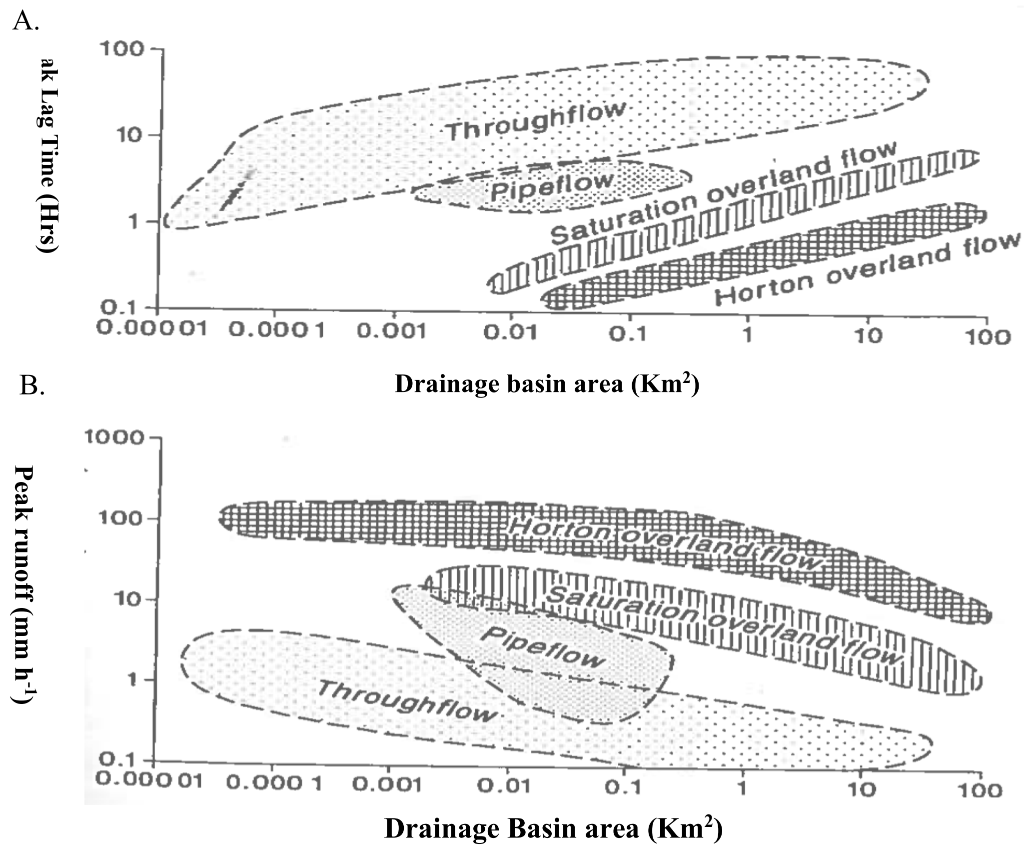


Figure 2.3 showing the relative response of hillslope drainage processes based on catchment size. Figure 2.3A shows the relative responses in relation to Lag time, while Figure 2.3B shows the relative responses in relation to Peak runoff (Jones, 2000b).

2.3.2 Drivers/Causes of Flooding

The drivers or causes of flooding can be grouped into direct and indirect drivers. Ultimately, precipitation (in the form of rainfall or snowmelt) is widely regarded as the direct driver of urban floods (Heggen *et al.*, 1996; Reddy, 2005). Whether urbanisation is a direct or an indirect driver of urban flooding is still a debate (Gupta and Nair, 2011; Hashizume, 2013). As stated above, urban floods result from the combination of flow regimes. They result from the interaction of meteorological and hydrological extremes (Jha *et al.*, 2012). Heggen *et al.* (1996), argued the difference between direct and indirect drivers should depend on whether it was generated by climatic or non-climatic factors. Jones (2000a) argued that the sources or drivers of floods can be classified as 'natural' if caused by natural factors e.g. rainfall or snowmelt, or humans if influenced by modifying factors such as urbanisation or deforestation (see Table 2.2). In this study, urbanisation, or land-use change, is considered an indirect driver because it does not initiate but rather modifies the hydrologic process.

Table 2.2 showing the category of inputs or factors that cause and modify floods. The major inputs are Natural, Human, Watershed Characteristics/Hillslope properties. Land surface changes result mainly from urbanisation, deforestation, afforestation and agriculture (Jones, 2000b).

Input	Category	Sources
Natural	Initiating factors	Natural inputs or initiating factors: such as heavy rainfall and rapid snowfall
Human	Modifying factors	Land surface changes result mainly from Urbanisation Deforestation Afforestation and agriculture. Engineering/Planning e.g. Dam Construction, River regulation
Watershed Characteristics/Hillslope properties	Physiographic	Basin morphometry Watershed or hillslope properties Channel properties

In the context of flood risk, Wheater and Evans (2009) divided flood risk drivers into eight driver groups based on climatic, natural, socio-economic systems and processes as well as human behaviour (see Table 2.3). The driver group consists of climate change, catchment runoff, Groundwater systems and processes, fluvial systems and processes, urban systems and processes, coastal processes, human behaviour and socio-economics. The table indicates that climate change is the main driver at source through precipitation, temperature, waves, surges and rises in sea level. The flood risk pathway is affected by natural systems and human behaviour and, importantly, through urbanisation, rural land management, environmental regulation, coastal morphology and so forth. While climatic factors cannot be controlled, there is scope for managing human-induced causes such as urbanisation, environmental regulation and land management. Moreover, Figure 2.4 shows another diagram of the flood system showing a connection of source pathway, receptor and consequences of floods.

Table 2.3 showing a list of Fluvial/coastal and intra-urban drivers groups. Driver group include Climate change, Catchment runoff, Groundwater systems and processes, Fluvial systems and processes, Urban systems and processes, Coastal processes, Human behaviour and Socio-economic driver groups (Wheater and Evans, 2009). Note SPR means source, pathway and receptor of flooding respectively.

Driver group	Driver	Classification
Climate change	Precipitation	Source
	Temperature	Source
	Relative sea-level rise	Source
	Waves	Source
	Surges	Source
Catchment runoff	Urbanisation	Pathway
	Rural land management	Pathway
Groundwater systems and processes	Groundwater flooding	Pathway
Fluvial systems and processes	Environmental regulation	Pathway
	River morphology and sediment supply	Pathway
	River vegetation and conveyance	Pathway
	Urbanisation and Intra-urban Runoff	Pathway
Urban systems and processes	Sewer conveyance, blockage and sedimentation	Pathway
	Impact of external flooding on intra-urban drainage systems	Pathway
	Intra-urban asset deterioration	Pathway
Coastal processes	Coastal morphology and sediment supply	Pathway
Human behaviour	Stakeholder behaviour	Pathway
Socio-economics	Buildings and contents	Receptor
	Urban impacts	Receptor
	Infrastructure impacts	Receptor
	Agricultural impacts	Receptor
	Social impacts	Receptor
	Science and technology	Receptor

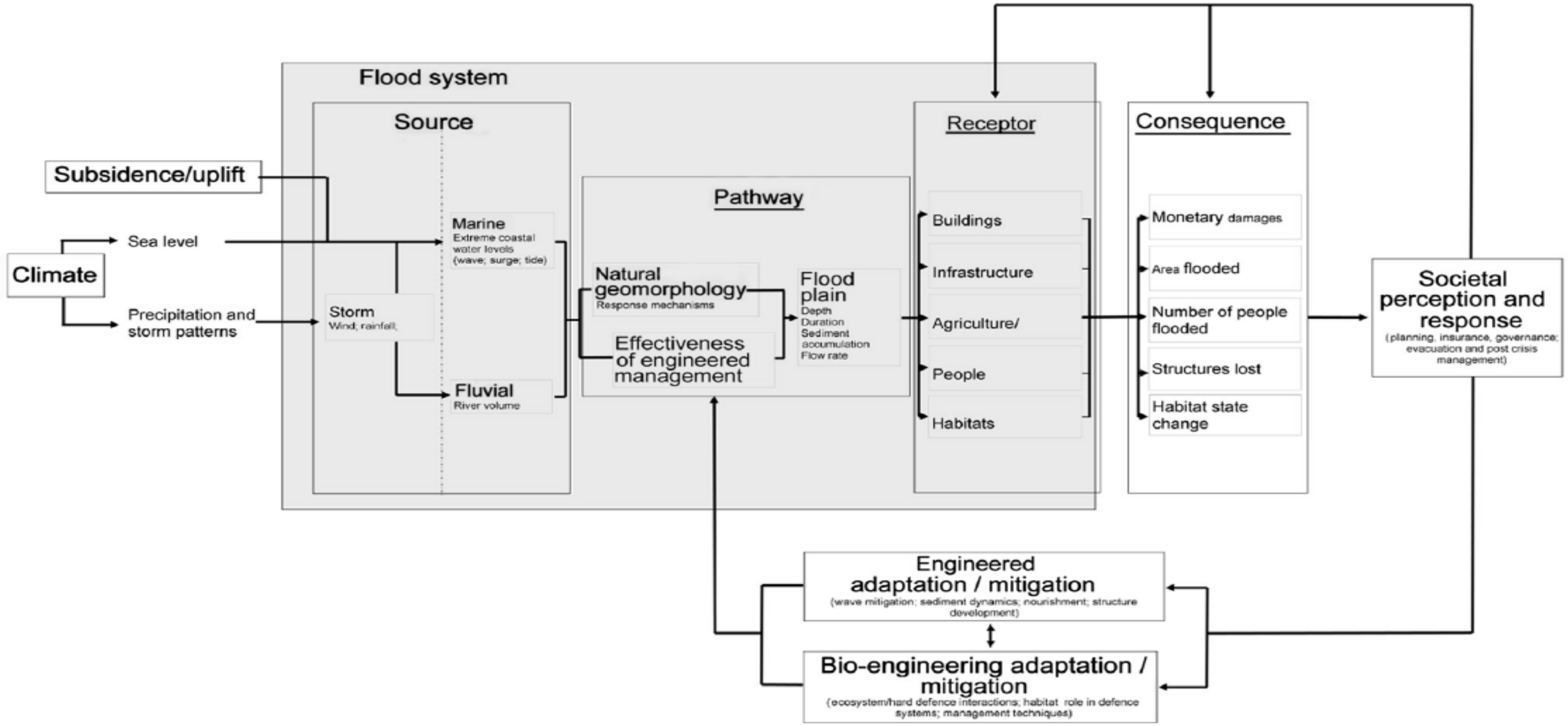


Figure 2.4 showing a flow diagram of Source-Pathway-Receptor-Consequences (SPRC) of a Flood system. External factors at source include precipitation. The main characteristics of flood in the flood pathway included flood depth, flood velocity, flood extent. The main elements at risk include buildings, infrastructure, agriculture and habitats (Source; Narayan et al., 2014).

2.3.3 Urban-Related Flood Research.

Urban flooding, resulting from extreme runoff, has been extensively researched as a planning, watershed and disaster management problem (Tang *et al.*, 2005; Baloch *et al.*, 2015) and (Chow, 1959; Brooks, 1985; Beven and Carling, 1989; Lazaro, 1990; Heggen *et al.*, 1996; Parker, 2000b). Broadly, these studies hold that flooding is a product of the interaction of environmental (physical) and social processes, in this case, the interaction between heavy rainfall and urbanisation. Urban flood research has intensified since the 1960s due to increased understanding of hillslope hydrology and open channel hydraulics (Lazaro, 1990; Akan, 2006). As indicated in chapter 1, several aspects of urban flooding have been extensively documented and are understood (Leopold, 1968; Beard and Chang, 1979). These studies can broadly be grouped into six categories.

Table 2.4 Forms of flood research identified in Literature. Different types include Research on Sources/ Drivers/Causes of floods, Effects/impact research, Flood modelling research, Flood hazard research, Flood vulnerability research, Flood risk management research.

Type of Research	Sub-category	References
Research on Sources/ Drivers/Causes of floods	Direct	(Heggen et al., 1996)
	Rainfall	(Beven and Carling, 1989),
	Snow melts	(Heggen et al., 1996)
	Indirect	(Heggen et al., 1996)
	Urbanisation	(Lazaro, 1990)
	Environmental regulations	(Wheater and Evans, 2009)
Effects/impact research	On infiltration	(Brakensiek and Rawls, 1994)
	On base flow	(Hamel et al., 2013)
	On streamflow	(Beard and Chang, 1979)
	On catchment runoff	(Du et al., 2012)
	On water quality	(Tong and Chen, 2002)
	On sediment load	(Zuo et al., 2016)
	On erosion	(Biddoccu et al., 2016)

Type of Research	Sub-category	References
Flood modelling research	Hydrologic modelling	(Todini, 2007)
	Water quality modelling	(Cebe and Balas, 2016)
	Hydraulic modelling	(Van, 2010)
Flood hazard research	Flood hazard mapping	(Excimap, 2007)
	Flood hazard assessment	(Daffi et al., 2014)
Flood vulnerability research	Flood vulnerability assessment	(Koks et al., 2015)
	Flood vulnerability mapping	(Elalem and Pal, 2014)
Flood risk management research	Flood risk analysis	(Prinos, 2008)
	Flood risk assessment	(Nicholls et al., 2015)
	Flood risk control	(Islam and Ryan, 2016)
	Adaptation	(Parker, 2000b).

Despite the extensive research in these areas, a number of review studies have argued that there are important gaps in flood forecasting research (Cordery *et al.*, 2000; Parker, 2000a; Parker, 2000b; Arduino *et al.*, 2005; Pitt, 2008; Teutschbein and Seibert, 2010; Samuels, 2012). For example, Pitt (2008), Samuels (2012) and Jha *et al.* (2012) have emphasised the need to reduce the uncertainty arising from the acceleration of future climate changes and human activities in urban and coastal environments.

Samuels (2012) further stressed on the need for improved understanding of future flood forecasting, particularly on the need to reduce the uncertainty of the effects on flooding. Also on the need to estimate decadal timescale changes in floods and their impacts. Samuels (2012) likewise emphasised the need to understand the degree to which fluctuations in the intensity of extremes can be attributed to natural variability or anthropogenic influence. Other studies have also stressed the need for an extensive study on ungauged catchments in regions with limited resources e.g. Africa (Parker, 2000b; Osti *et al.*, 2008; Kusangaya *et al.*, 2014).

Cordery *et al.* (2000), importantly underscored the need for improved estimates of flood magnitude in ungauged catchments such as in the Greater Port-Harcourt Basin where streamflow data has not been collected. According to Parker (2000b), flood prediction is often less complete and constrained in regions with limited resources such as in Africa. For example, despite the hydrologic sensitivity of the Niger Delta environment, majority of its rivers are still ungauged (Adeaga *et al.*, 2012), as such there are no available historical data. The lack of data and extensive research on the watershed, coupled with climate change projection and human activities in this region means there is huge uncertainty about the basin's hydrologic response to human-induced environmental changes.

Recently, researchers have utilised recently available satellite-based rainfall and geospatial datasets with cost-effective detection methods to assess flood hazards in ungauged regions (Li *et al.*, 2008; Roy and Mistri, 2013). Surprisingly, to date, the estimation of future flood effects is lacking in the Greater Port-Harcourt watershed. For example, there is presently no estimate of future catchment responses or effects on lag time, peak discharge or runoff volume found in the study for this catchment. Moreover, the linearity of the catchment response has never been discussed. Knowledge of the effect effects on important hazard parameters such as flood depth, velocity or extent**,** duration and so forth is very scanty. There is also no knowledge of the damage potential of floods and priority areas for flood risk management. Hence, accepting the generalisations from studies of other catchments in previous studies such as Leopold (1968) and Hollis (1975) can be confronted by differences in the nature and size of catchments, which may lead to inaccurate predictions (Hollis, 1975). Therefore, the need to understand the individual catchment response to future climate and urban land-use changes is essential for one of the most sensitive wetlands in the world. The need to understand priority areas for flood risk management is also essential for flood risk mitigation.

More broadly, in terms of effects of development alternatives, DEAT, (2004) and Glasson *et al.*, (2005) have argued that the choice of project alternatives can have implications for land-use, see section 2.7.4. But despite the plethora of flood-related research in the field, there is little or no published work on the potential effects of location alternative on catchment or sub-catchment hydrology (to the best of the author's knowledge). Research in this area could help improve understanding of important hydrologic factors to consider when choosing alternative locations for developments. Again, there are still gaps in knowledge in terms of the potential effects of land-use changes and storm in GPH watershed**.** There are also knowledge gaps in terms of future priority areas at risk of flooding.

Box 2.1 Relevance for this Research.

A gamut of urban flood related studies exist that cover various aspects such as sources/drivers/causes of floods, effects/impact of floods, modelling, flood hazard, flood vulnerability and flood risk management. Despite the coverage, the GPH watershed is under-researched. Catchment responses vary from catchment to catchment. The future impact of urbanisation and climate change on flooding is poorly understood in this studied area and there are uncertainties about future priorities for flood risk management in the area. Hence, insights from existing studies on e.g. causes of flooding, effects, modelling are crucial for understanding and comparing catchment responses in the study area.

2.4 THE EFFECTS OF URBANISATION ON FLOODING.

2.4.1 Effects of Urbanisation on Watershed Hydrological Parameters.

Theoretically, urbanisation, channel modification, deforestation and agriculture, as well as environmental regulation can all affect hydrologic processes and lead to flooding (Heggen *et al.*, 1996; Jones, 2000a; Phillips, 2002). Compared to other causal factors, a number of studies have demonstrated that urbanisation causes the most drastic effects on flooding (Leopold, 1968; Jones, 2000a; Parker, 2000a; Zuo *et al.*, 2016). According to Leopold (1968), of all land-use changes that affect the hydrology of a catchment, urban land-use change is the most forceful. This phenomenon results from increased impervious surfaces through land-use changes after urbanisation (Heggen *et al.*, 1996). Urbanisation can have severe implications for the hydrologic functioning, or magnitude, and frequency of floods (Lazaro, 1990) and flood plains (see Figure 2.5).

Currently, there are a plethora of studies covering this subject which reflects the level of research interest in this area (White and Greer, 2006; Hejazi and Markus, 2009; Du *et al.*, 2012; Suriya and Mudgal, 2012; Tripathi *et al.*, 2014). In the past, urbanisation has generated measurable effects documented in studies (Leopold, 1968; Hollis, 1975; Booth, 1991; Moscrip and Montgomery, 1997; Poff *et al.*, 1997). Early research, e.g. Leopold (1968) revealed that flooding is affected by two principal factors: percentage of impervious surface and rate of flow into channels. The net effect of these changes is that a higher proportion of precipitation is translated into a higher runoff, which generates faster quick flows. Generally, these studies agree that urbanisation lead to higher quick flows and are characterised by increased flood magnitude and frequency.

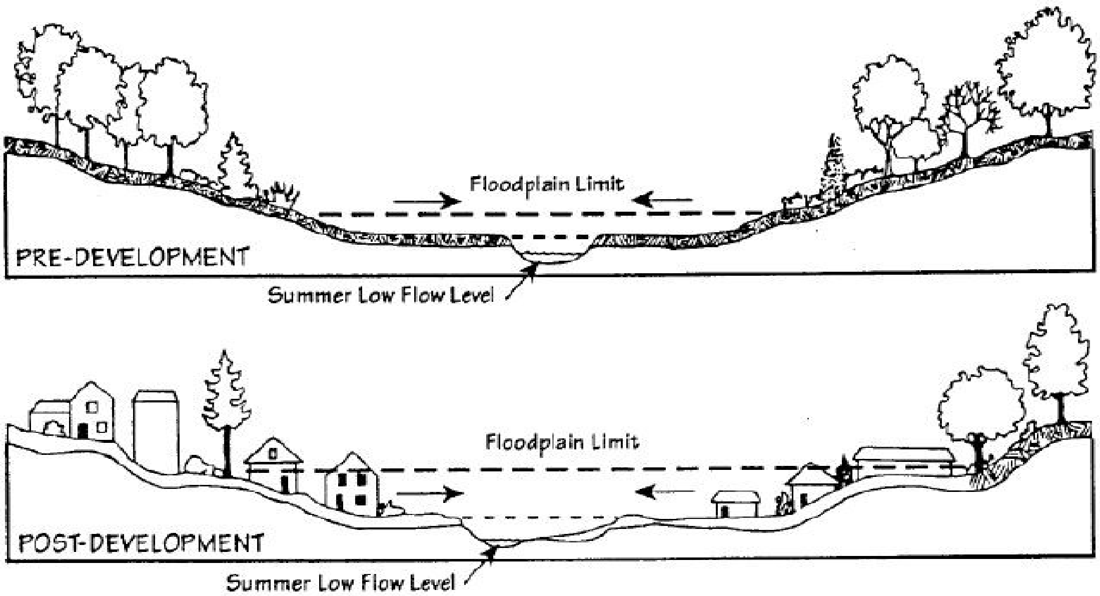


Figure 2.5 Diagrams showing the difference in the level of pre and post-development flooding in a floodplain. (Ramachandra and Mujumdar, 2009).

The effects of urbanisation are very complex. Their effect depends on prevailing flow regimes and other hydrologic factors. Examples of some key published work include studies on: the Sacramento Creek in California, by James (1965); Charlotte in North Carolina, by Martens (1968); Catchments in North East USA, by Lull and Sopper (1969); Wairau Creek, Auckland in New Zealand, by Williams (1976); Cannon's Brook Catchment in Essex, by Hollis (1974); Sawmill Brook Catchment in New Jersey, by Arnold *et al.* (1982). Although they arrived at different conclusions in terms of the magnitude of change there is a consensus that urbanisation leads to increased runoff (Figure 2.5). The majority of these studies agree that the impact of urbanisation is more significant for small floods and small basins.

In addition to increased runoff, urbanisation also leads to increased runoff volume, reduced infiltration, baseflow, lag time, time to peak and ground water storage (Heggen *et al.*, 1996; Chen *et al.*, 2009; Ali *et al.*, 2011; Du *et al.*, 2012; Verbeiren *et al.*, 2013). For the effects on discharge hydrograph and lag time, see Figure 2.6. Other studies have also demonstrated that alteration of land-use character affects direct runoff and total runoff and low flows (Booth, 1991). Generally, peak discharge (Q_p), peak volume (VP) and time to peak (T_p) are widely used as key parameters for measuring the hydrologic impacts on flooding.

Importantly, analysis in these studies have shown that the impact of urbanisation varies from catchment to catchment. This presents some complexities, in that some generalisations have been made in studies by Leopold (1968), but are confronted by different hydrologic factors and the natural variability of the individual catchments (Heggen *et al.*, 1996; Parker, 2000a). This implies that generalising effects across arid, semi-arid and tropical catchments from existing studies may not be accurate. Figure 2.6 is a sketch of hydrologic responses to urbanised and unurbanised catchments.

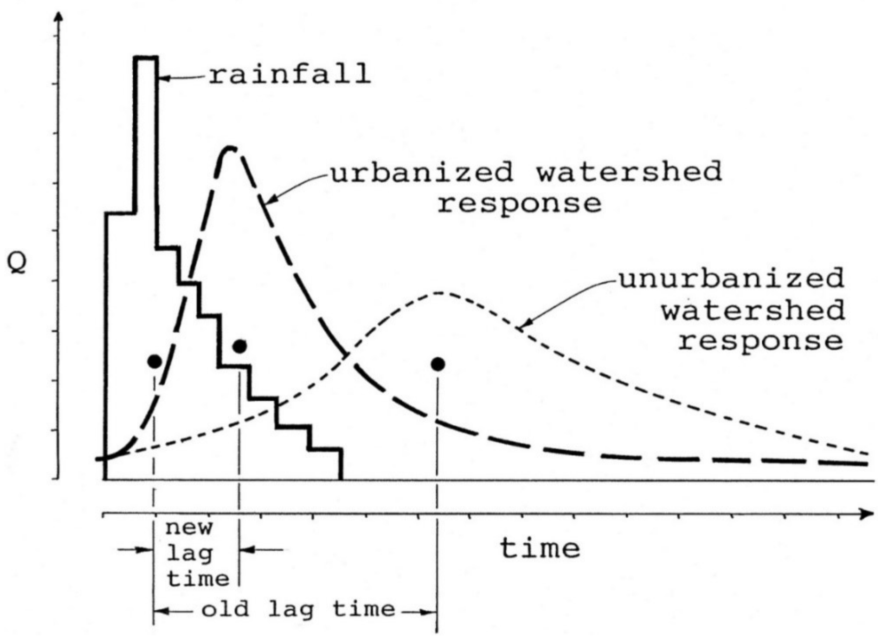


Figure 2.6 Sketch of two hydrographs showing different effects on peak discharge and lag time in un-urbanised and urbanised watersheds. The urbanised watershed response with higher peak and shorter lag time (Rogers, 1997).

2.4.2 Findings in Review and Existing Studies.

Since the 1960s, a number of review studies have synthesised results from a large number of studies in an attempt to generalise the impacts of urbanisation (Shuster et al., 2005; Chin et al., 2013; Leopold, 1968; Hollis, 1975; Fraser, 1977; Du *et al.* (2012). These studies generally agree that urbanisation can drastically change the flood peak discharge, however, their conclusions differ. For example, Leopold (1968), made a valuable contribution and a bold generalisation in his study entitled *Hydrology for Urban Land Planning-A Guidebook for the Hydrologic Effects of Urban Use.* Based on the synthesis of a large number of studies, he was able to relate the percentage of catchment sewered and impervious surface to post-urbanisation increase in mean annual flood in the study area. Two main graphs were produced from this work (see Figure 2.7 and Appendix 2.1).

As shown in Figure 2.7, Leopold (1968) found that increases in mean annual flood could rise between 1.5-6 times. This dispelled the idea of single ratio found in earlier studies. However, Leopold’s generalisation was fraught with limitations as the findings were not very useful for urban or regional planning because they are restricted in application to catchments less than $2.59km^{2.}$ (Hollis, 1974). Moreover, of particular interest to planners are high magnitude floods with potentially damaging impacts, e.g. 1/100 years floods (Hollis, 1974), but Leopold’s work only considered 1 in 30 years floods. This suggests that research into the effects of urbanisation must consider impacts of scale and magnitude relevant to planning.

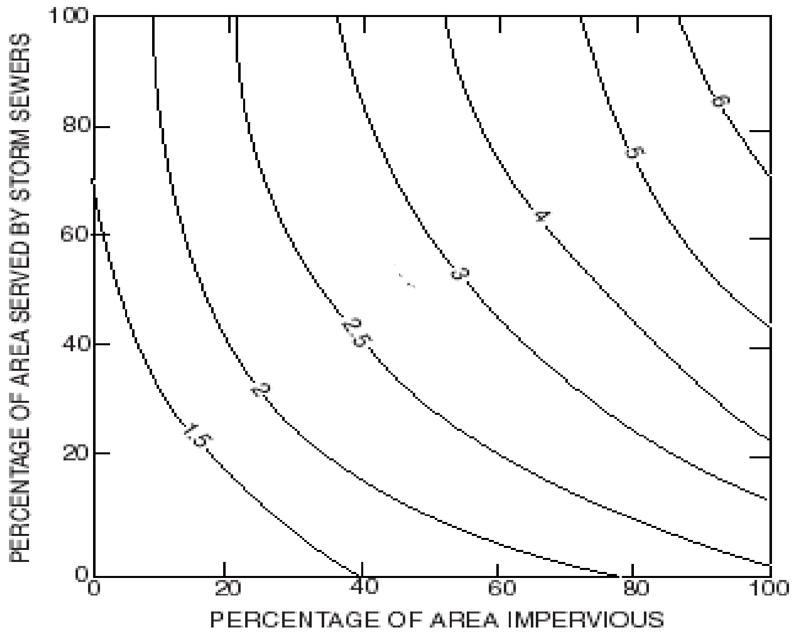


Figure 2.7 Effect of urbanization on mean annual flood for a 2.59 km^2 drainage basin. Values in the graph are the ratio of post-urbanisation peak discharge to pre-urbanisation peak discharge (Leopold, 1968).

Subsequently, Hollis (1974) made another valuable contribution to the field. He also concluded that urbanisation can drastically change the flood characteristics. Hollis (1974) critically examined Leopold’s work to better generalise the relationship between the increase in urban-induced flooding and the percentage of impervious surface (PctImp) and recurrence interval (T). Hollis (1974) finally derived a family of curves based on values of the ratio of peak discharge after urbanisation to peak discharge before urbanisation. The study was also a synthesis of a large number of studies, see Appendix 2.2.

It was found that the impact of urbanisation does not affect floods of different return periods to the same degree. Based on the ratio curves, Hollis (1975) further asserted that frequent small floods increase significantly in catchments due to urbanisation. The study also concluded that large floods rarely increase significantly due to urbanisation. Hollis (1975) argued that:

(1) Catchments with PctImp of 5% do not affect floods with less than 1yr return period, whereas those with PctImp of 30% may double the size of floods with a 100yr return period.

(2) Small floods may be increased by 10 times due to urbanisation.

He concluded that the effect of urbanisation is relative, such that the effects of urbanisation diminish as the return period increases. This raises a question what are the effect of future urbanisation on runoff in the GPH area based on the implementation of the GPH Masterplan?

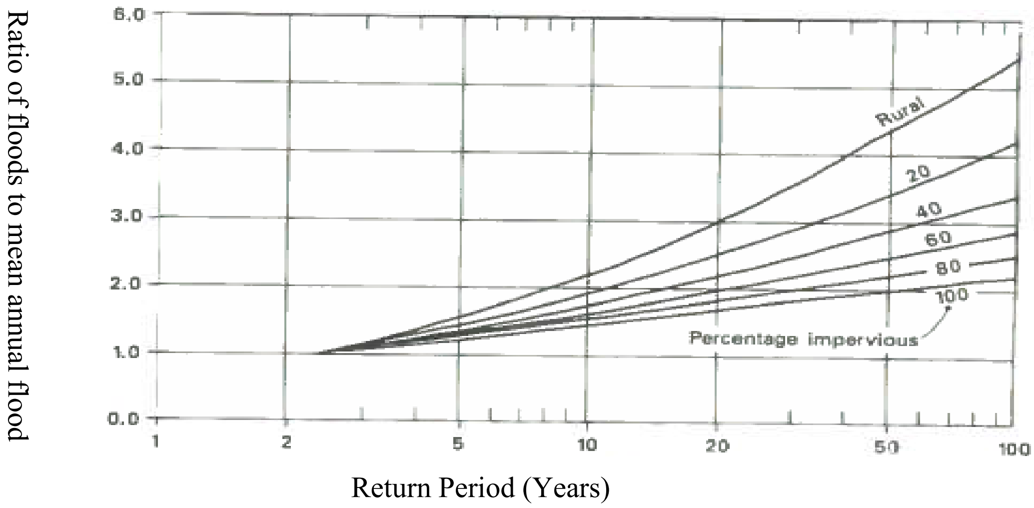


Figure 2.8 Effects of urbanisation on discharge for floods of different Return Period. (Anderson, 1970).

In contrast, Kuprianov (1977) found a 10% increase in average discharge in an experimental work in Minsk, Belarus, whereas Lvovich and Chernishov (1977) found a four-fold and two-fold increase in the suburban and the metropolitan areas in Moscow respectively. The study also found a 50% increase in the Moscow River. In Britain, Gregory (1974) found a two to three-fold increase due to suburbanization of Exeter Catchment. The work of Gregory (1974) and Hollis (1979) both showed that summer storm flows were enhanced more than winter storm flows which may be explained by higher convective storm events during the summer months that are twelve times larger. Generally, these studies emphasise a greater increase in peakedness as well as an increase in frequency and magnitude of stormflows with storms of smaller return periods. However, urbanisation impacts on flood magnitude vary in the studies.

Again, in spite of these valuable contributions, Yucel (1974) argued that the effects of urbanisation cannot be analysed solely based on the percentage of impervious surface, but should include the position of development within the catchment. This means generalisations in Leopold (1968) and Hollis (1975) cannot be used to draw conclusions since land-use patterns, physiographic characteristics, location or position of developments and other explanatory variables in different catchments vary. It means that generalisations based on experiments and the synthesis of results from catchments may be misleading if applied to other catchments.

2.4.3 Urbanisation Effects on Flooding in Arid and Tropical Catchments in Developing Countries.

Since the 1980s, there has also been increased attention on arid and tropical catchments in developing countries (Hamilton *et al.*, 1983; Bruijnzeel, 2004; Ali *et al.*, 2011; Halwatura and Najim, 2013; Hegazy and Kaloop, 2015). Nonetheless, runoff generation in the tropics is more complex to understand. It begs for improved understanding at the catchment level. For example, overland flow tends to be the dominant flow regime in arid climates, and flow regimes in moist tropical catchments tend to originate at least from saturation overland flow and overland flow, depending on antecedent moisture content (Booth, 1991; Parker, 2000a). This makes it rather more complex.

Existing research on the effects of urbanisation in tropical catchments by Bruijnzeel (1990), similarly showed increased peak flows for small events. Another work by Ithnin (1992), on the effects of urbanisation on small stream catchments in Kuala Lumpur, similarly showed increased peak discharges. Despite the growing number of studies, Parker (2000a) argues that catchment examination in developing countries is less intense than in developed countries. Since the degree of impact varies widely across regions and catchments and is dependent on the mechanisms that dominate that particular area, there is, therefore a need to understand the future catchment response to urbanisation.

2.4.4 Findings in Recent Studies.

Recent studies have advanced knowledge of the effect of urbanisation on flooding. They include Brilly *et al.* (2006); Du *et al.* (2012); Suriya and Mudgal (2012); Miller *et al.* (2014); Tripathi *et al.* (2014); Ali *et al.* (2011); Oleyiblo and Li (2010); Halwatura and Najim (2013). Comparatively, the majority of older studies assessed the effects of urbanisation from a historical standpoint (using the ‘before and after’ approach). In contrast, today there is increased interest in the future impacts of urbanisation on flooding. They often utilise available modelling and scenario methods (McColl and Aggett, 2007; Ali *et al.*, 2011; Du *et al.*, 2012; Samuels, 2012; Halwatura and Najim, 2013). This may be due to increased awareness of the uncertainty about climate change and human activities. Du *et al.* (2012) assessed the historical effects of urbanisation in Qinghai River Basin (China) and found a 3.5% increase in peak flow due to a 17% change in urban land between 1988 and 2009. Meanwhile Dudley *et al*. (2001) found that there was no historical significant change in peak flows despite a large increase (161%) in the paved surface in a catchment situated in southern Maine, USA. Ali *et al.* (2011) and Du *et al.* (2012) both accessed potential impacts of urbanisation. Ali *et al.* (2011) found that future land-use as envisioned in the Masterplan is expected to raise the peak discharge significantly between 45.4 and 83.3% in the Lai Nullah Basin in Islamabad, Pakistan. Du *et al.* (2012) found that 11.8% and 14.0% expansion in built-up areas (based on year 2002 urbanisation) potentially could raise the peak discharge by 1.6% by 2020 and 3.3% by 2050 levels in the Qinghai basin in China. In nutshell, there is a large consensus that urbanisation affect peak discharge, however the degree of impact vary from watershed to watershed. What is not known is the degree to which urbanisation has affected runoff in past or could affect runoff in the future.

Box 2.2 Relevance for this Study.

The relationship between urban growth and runoff have been investigated in many studies. Leopold (1968) concluded that increase in small floods could rise between 1.5-6 times due to urbanisation. Hollis (1975) argued they may increase 10 times. In other catchments, Lvovich and Chernishov (1977) found a four-fold and two-fold increase in the suburban and metropolitan areas in Moscow, respectively. Kuprianov (1977) found a 10% increase in average discharge in an experimental work at Minsk Belarus. In Britain, Gregory (1974) found a two to three-fold increase due to suburbanisation of Exeter catchment.

Recently, Ali *et al.* (2011) demonstrated that a proposed land-use masterplan in Lai Nullah Basin, Pakistan may likely raise peak discharge between 45.5% and 83.3%. In Qinhuai River Basin, China, Du *et* al., (2012) showed that mean annual runoff would increase 5.6% from 2018 level, when impervious ratios change from 3% (1988) to 31% (2018). Similar studies of future effects in 2017 are non-existent for the Greater Port-Harcourt area and application of the above generalisations may not be accurate for the GPH watershed due to variability of basin conditions. Therefore, there is a need to understand effects in this study area.

2.4.5 Urbanisation Effects on Runoff: Studies in the Niger Delta.

Although a number of flood related studies have been conducted in the Niger Delta (Chiadikobi *et al.*, 2011; Elenwo and Efe, 2014; Akukwe and Ogbodo, 2015), the majority of the studies are focused on historical impacts. Flood-related studies in the area can be grouped into two. Firstly, those focused on the identification and review of causes and effects of flooding (Abam, 2001; Bariweni *et al.*, 2012; Elenwo and Efe, 2014; Akukwe and Ogbodo, 2015; Ikechukwu, 2015). The majority of these studies attribute increased flooding to lack of or inadequate, drainages, urbanisation, heavy rainfall and topography. There is yet to be a published work on the future impacts of urbanisation. Secondly, the other set of studies focused on the vulnerability of receptors to flooding (Eludoyin and Weli, 2012; Akukwe and Ogbodo, 2015). Akukwe and Ogbodo (2015) found that flood vulnerability increases towards the Northeast and Southwest of Port-Harcourt City. Generally, no contribution have been made in terms of estimating the impact on flooding due to future urbanisation or even climate change. According to Jha *et al.* (2012), understanding future effects of flooding has particular benefits in supporting planning and adaptation to climate change as well as the wider coastal management of the area.

2.5 EFFECTS OF CLIMATIC FACTORS ON FLOODING.

Climate change is increasingly having severe implications for the hydrological cycle, both at global and local scales (Metz *et al.*, 2007; IPCC, 2013). With observed increases in average surface air temperature (by 0.6 °C) since the beginning of the 20th Century, climate change affects precipitation patterns, especially its intensity, frequency, duration, and distribution (Khon *et al.*, 2007; IPCC, 2014; Tofiq and Guven, 2014). Rainfall remains the primary driver of variability in the water balance over space and time and has very important implications for flooding (Heggen *et al.*, 1996; Bathurst *et al.*, 2011). However, the characteristics of rainfall in a region do not solely depend on local climate and atmospheric circulation, but also on proximity to oceans and local physiography (Cordery *et al.*, 2000). Recently, a number of studies have examined the effects of storm extremes on flooding (Hejazi and Markus, 2009). Generally, recent studies hold the view that changes in flood characteristics are more dependent on climatic factors like rainfall than on non-climatic factors (Heggen *et al.*, 1996; Jones, 2000a; Franczyk and Chang, 2009). In addition, they advocate that the effects on runoff in large basins are primarily dependent on storm size rather than land-use. On the other hand, runoff in small basins both depend on land-use and storm size.

Furthermore, hydrologic variability over time in a catchment is influenced by variations in precipitation over daily, seasonal, annual, and decadal time scales (Heggen *et al.*, 1996). In the tropics, extreme events result from either large weather frontal systems or local convective systems, all dependent on atmospheric temperature (Heggen *et al.*, 1996). According to Cordery *et al.* (2000), the magnitude of the impact of rainfall varies widely and much misinformation is generated by researchers who claim the generality of the processes. Therefore, local and regional examination of the effects of future climate is required for the Niger Delta region.

2.5.1 Prediction of Climate Change Effects on Flooding.

Predictions of climate change impact on flooding in the dynamic future world are predominantly based on scenarios in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) report (IPCC, 2000; Djordjević *et al.*, 2011; IPCC, 2012, 2014). The Greenhouse Gas (GHG) scenarios are a central component of any assessment of climate change based on a reproducible set of assumptions on the driving forces of change (IPCC, 2000). They entail different storylines based on population, economic development, structural and technological changes in which the future may evolve. There are four main scenario families (A1, A2, B1, and B2) and six markers (A1FI, A1T, A1B, B1, A2 and B2) which are used as inputs in the complex Global Circulation models (GCMs), (IPCC, 2000). Although, GCMs can be downscaled for Regional Climate Models (RCM), in this study, outputs of GCMs has been downscaled for Local Climate Models (LCMs), (McSweeney *et al.*, 2010).

An important projection contained in the IPCC reports is that the global average annual precipitation is likely to rise, although changes will vary from region to region. Today, global models project increase and decrease in precipitation throughout the year in high and low latitudes respectively, with considerable disagreement between models for the tropics (Metz *et al.*, 2007; UNFCCC, 2007; IPCC, 2012, 2013). Generally, precipitation is projected to be more variable, however, it projected to experience greater extremes (IPCC, 2012, 2013). The disagreement in models brings greater uncertainty. However, precipitation is the main cause of flood and greater extreme mean the watershed is likely to experience higher runoffs and flooding.

2.6 FOREST AND URBAN FLOODING.

A good number of studies have also looked into the effects of forest on flooding and water yield (Robinson, 1986; Sahin and Hall, 1996; Lane *et al.*, 2005; Bathurst *et al.*, 2011; Brown *et al.*, 2013). Forests can play a role in flood mitigation and watershed management because of forest effects on evaporation losses and reduction of peak discharge (Brooks, 1985; Lane *et al.*, 2005; Buytaert *et al.*, 2007). While these effects have been widely investigated, the extent to which forest can reduce flood is controversial. The precise mechanism that governs them is still unclear. For instance, it is still debated whether catchments draining to reservoirs should be predominantly forest or grassland (Sahin and Hall, 1996) and whether the level of peak flow under mature forest is higher (Robinson and Newson, 1986), or lower (Binns, 1979) than that from the original moorland. In any case, the catchment response to forest land-cover is also dependent on forest types, forest maturity and antecedent moisture content (Brown *et al.*, 2007; Brown *et al.*, 2013).

Studies on forest effects include reviews of previous experiments, notably the work of Hibbert (1967), and Bosch and Hewlett (1982). Others include effects on tropical rainforest e.g. Bruijnzeel (1990) and more recently, Zhang *et al.* (1999), Best *et al.* (2003) and Andréassian (2004). Many of these studies agree that afforestation reduces mean annual discharge and water yield, while a few other studies disagree with this view. Other non-review studies, such as Scott and Lesch (1997), showed that eucalyptus afforestation in a catchment caused a statistically significant decrease in streamflow after the ninth year. With respect to the pines, the study similarly showed afforestation produced a significant decrease in streamflow in its fourth year. Most publications describe the dynamics in small catchments, with fewer studies focusing on large catchments. It is unclear as to whether the findings for small catchments can be applied to large catchments.

In large catchments, catchment response to afforestation or deforestation is more difficult to generalise. For example, a large catchment study by Bart and Hope (2010) showed that the effects of deforestation on streamflow due to fire was variable. Hence, an increase in streamflow was largely dependent on post-fire wetness conditions rather than deforestation. Another large, tropical catchment study in Thailand by Wilk *et al.* (2001) was unable to distinguish any hydrologic changes attributable to the reduction in vegetal cover. For large basins, Siriwardena *et al.* (2006) argued that consensus has not been reached on the effects of forests on flow due to spatial and temporal variability and differences in the stages of forest regeneration.

Greater Portharcourt forms part of a coastal tropical mega delta undergoing rapid urbanisation. What we don’t know in the Greater Portharcourt area is the extent to which afforestation could reduce flooding? Robinson and Newson (1986) suggested that the magnitude of increase in flow peaks depends on both the duration and shape of the rainfall profile. Port-Harcourt has a tropical climate and rainfall is significant most months of the year (NIMET), at the same time its upstream areas contain rainfaorest zones. The area also has a high drainage density. The question is can more forest in the area reduce flooding? What storm conditions could afforestation mitigate flooding? Hence, there is a need for improved understanding of the capacity of the forest to mitigate flood in different storm conditions.

Box 2.3 Relevance for Study

The drainage area of the GPH portion of the Niger Delta River Basin is approximately 4800 km^2. In terms of land-cover, the Northern axis of the City housing the GPH development is covered by low-land rainforest vegetation. Forest cover directly affects the rates of transpiration and evaporation. It reduces evapotranspiration and interception losses by eliminating transpiration and evaporation from the elevated canopy. Consequently, changes in forest structure can alter hydrologic processes in space and time. While the effects of forest in small catchments is well known, the effect in large basins vary depending largely on rainfall. Knowledge of catchment response to afforestation is very scanty for the studied watershed but it is critical for flood risk and watershed management purposes.

2.7 FLOOD HAZARD.

2.7.1 Flood Hazards in Risk Analysis.

The 'hazard paradigm' has dominated the risk and disaster fields for much of the twentieth century in which flood and other hazards are viewed as a natural phenomenon (Parker, 2000b). To date, concepts and definitions of environmental risk often vary and are subject to intense debate (Whyte and Burton, 1980; Plate, 2002; Koks *et al.*, 2015). For example, the presence of a hazard or danger is sometimes used to mean environmental risk (Whyte and Burton, 1980). In other cases, risk it has been used more narrowly to mean the probability of elements to suffer adverse consequences or the chance of encountering some loss (Nicholls *et al.*, 2015), (IPCC, 2012; Koks *et al.*, 2015). Flood hazard is defined as the probability and magnitude of the occurrence of a potentially damaging flood (Koks *et al.*, 2015), see Figure 2.9. Vulnerability refers to the inherent characteristics of elements which determine their potential to be harmed (Schanze, 2006). Exposure is viewed as a subset of vulnerability and refers to the measure of the elements at risk in flood vulnerable zones (Parker, 2000b; Balica *et al.*, 2009). Generally, flood risk is expressed as a function of hazard and vulnerability (Koks *et al.*, 2015; Nicholls *et* *al.*, 2015). It then suggests that flood risk is the product of environmental and societal processes, whereby flood is the physical agent (hazard) that poses a threat to society.

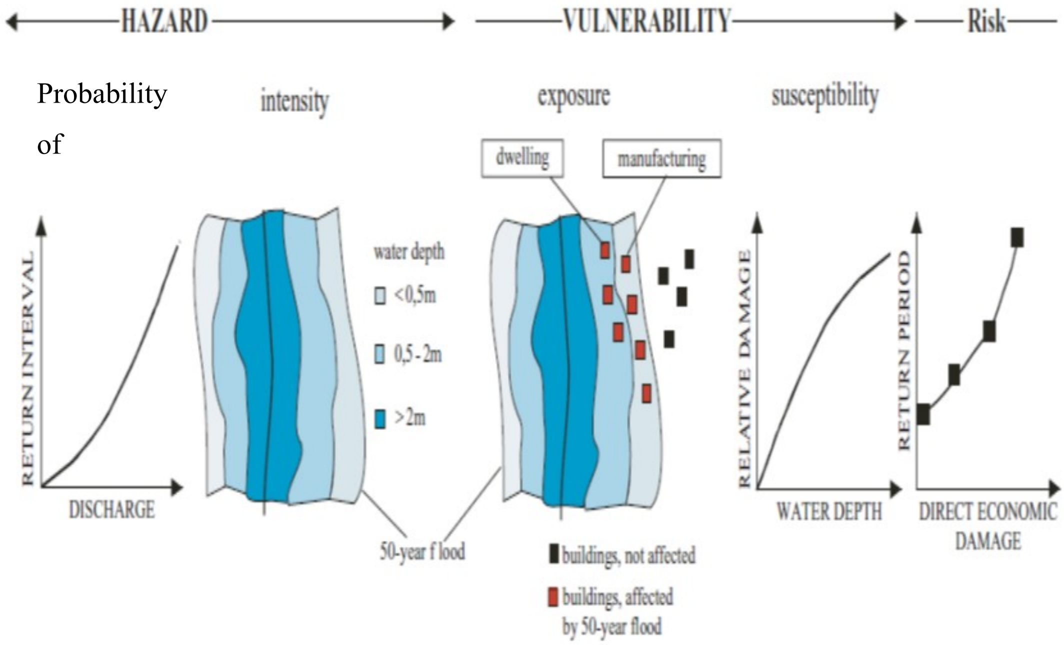


Figure 2.9 Flood risk as interaction of hazard and vulnerability. Darker colours show greater intensity on the hazard diagram (Merz *et al.*, 2007b).

To date, a number of measurable characteristics have been widely used to predict the impact on flood (Heggen *et al.*, 1996; Parker, 2000b; Nicholls *et al.*, 2015). These flood hazard characteristics are also known as flood hazard parameters, used in flood hazard, vulnerability and risk mapping, see illustration in Figure 2.9. They include peak discharge, peak runoff volume, and rainfall-runoff, lag time (Parker, 2000b). In rivers, they include flood depth or water surface profile, flood extent, flood velocity and flood duration (Moel and Aerts, 2011; Nicholls *et al.*, 2015). To date, there have been inconsistencies in the set of parameters applied in studies. Some studies only investigate impacts with one or two parameters at a time (Knebl *et al.*, 2005; Oleyiblo and Li, 2010). However, peak discharge, flood depth, flood extent and flood velocity are the most commonly used parameters or indexes.

Flood depth has direct implications for humans. A large number of studies have demonstrated that flood depth of 1m or more, even with low-velocity, is sufficient to cause damage to any built-up area if it stays for some time (Schanze, 2006; Duan *et al.*, 2009; Moel *et al.*, 2009; Koks *et al.*, 2015) which could partly be due to buoyancy effect (Duan *et al.*, 2009). Conversely, flood waters of less than 1m meter with greater velocity can generate serious risks to humans, as illustrated in Figure 2.10 and 2.11 (Parker, 2000b; Duan *et al.*, 2009). Flood velocity is another important parameter. Flood velocity, equal to or greater than 0.5 m^2/s, is considered critical both to life and property (Schanze, 2006). Flood peak discharge is the most common method of predicting changes in magnitude. It is often derived from hydrographs with the aid of flow meters and/or model predictions (Chen *et al.*, 2009; Suriya and Mudgal, 2012).

Flood extent is a measure of importance used for modelling the effects and flow of floods (Parker, 2000b; Schanze, 2006; Excimap, 2007; Merz *et al.*, 2007a). It has been conceived in the above studies that the larger the flood extent, the larger the flood magnitude. Lag time is also an important parameter, often overlooked in modelling and hazard analysis studies, but according to Parker (2000b), it is an index for determining flashiness.

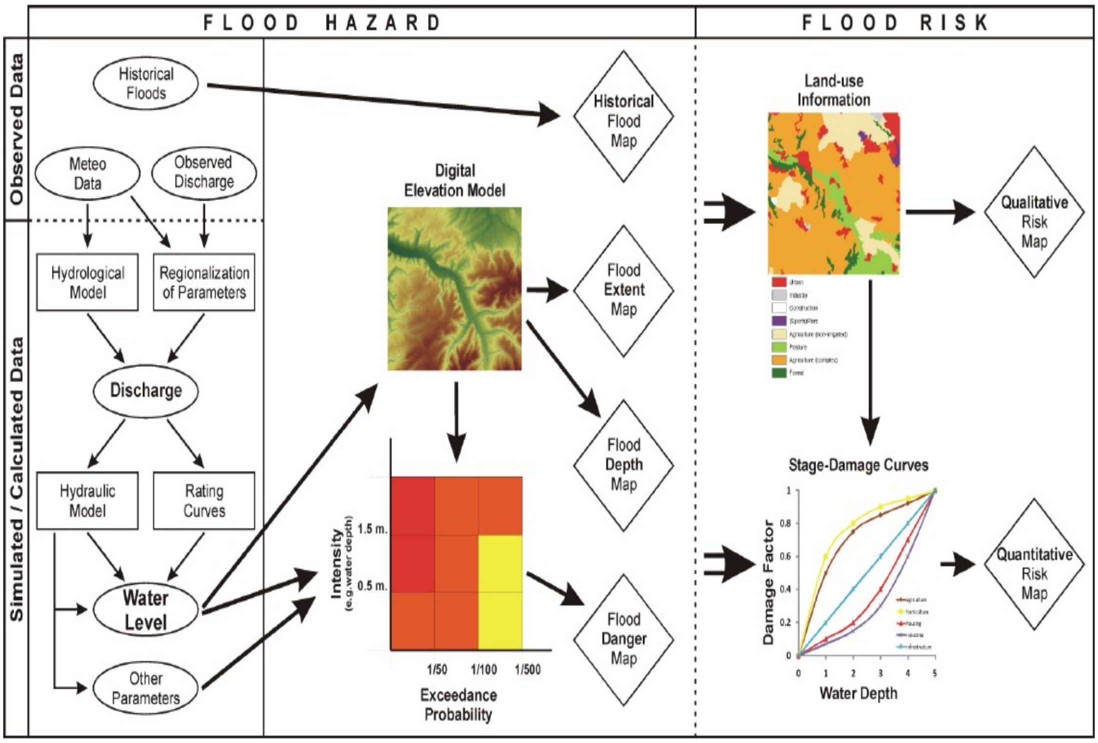


Figure 2.10 Conceptual framework for flood hazard and risk calculations. The displayed matrix and curves are purely illustrative and based on a hypothetical case. In the matrix, the yellow colour signifies low danger, the orange colour a moderate danger and the red colour, high danger (Moel and Aerts, 2011).

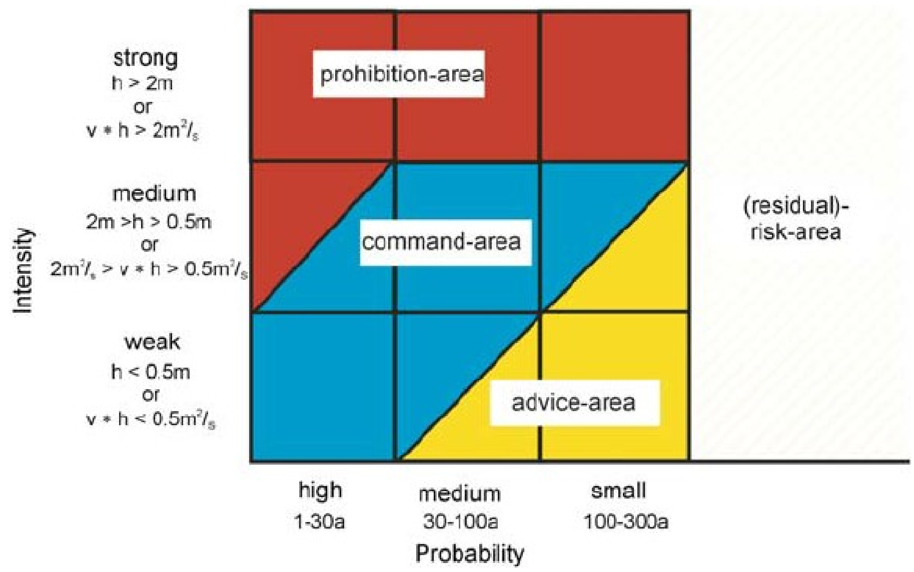


Figure 2.11 Intensity-probability-matrix for the assessment of hazard-prone areas (danger zones) as the basis for land-use planning in Switzerland. In the matrix, the yellow colour signifies low danger (advice) area, the blue colour represent moderate danger (or command) area and the red colourrepresents high danger or prohibited area (Merz et al., 2007).

Figure 2.11 shows the intensity-probability-matrix for assessing flood prone areas. In prohibiited areas, construction is generally not allowed. In command areas, construction is allowed under certain conditions. In advice areas, construction is possible, but recommendations are given. The residual-risk zones cover areas where natural processes might occur, but with a very small likelihood. Sensitive objects, e.g. schools, should not be built in such zones (Merz *et al.*, 2007a).

2.7.2 The Source-Pathway-Receptor-Risk Model.

To better understand the interaction between flood hazards and society in flood plains, the understanding of the source-pathway-receptor-consequence causal chain in risk analysis is important (Schanze, 2006; Nicholls *et al.*, 2015). The model shows a simple causal chain consisting of:

1. Source of hazards e.g. rainfall (climatic), land-use changes (fluvial)
2. Pathways (of hazards) e.g. depth, velocity, sediment
3. Receptors or elements at risk, e.g. people, properties, buildings, flora, fauna

4. Consequences e.g. monetary damage, the number of people, structures lost and habitat state change.

Figure 2.9 illustrates a causal chain from the source and pathway, including the physical process; receptors and consequences are defined by social values as displayed in Figure 6.2. (EC, 2001; Schanze, 2006; Excimap, 2007; Prinos, 2008; Moel *et al.*, 2009; Nicholls *et al.*, 2015). The SPRC model helps to differentiate the possible location of hazards. It also helps to differentiate types of hazard at source (e.g. Rainfall); impact on hazard parameters in the pathway (e.g. discharge or flood velocity) impacts on receptors (e.g. people) and impacts in terms of consequences (e.g. number of people).

2.8 URBANISATION, SUSTAINABLE PLANNING, ENVIRONMENTAL IMPACT ASSESSMENT AND ALTERNATIVES.

The fact that the world is undergoing an unprecedented rate of urbanisation is well documented in the literature (Lazaro, 1990; UN-HABITAT, 2005; Dye, 2008; Chen *et al.*, 2009; Suriya and Mudgal, 2012). In the1800s, only about 3% of the total population lived in urban areas (Dye, 2008). By the 1900s, this proportion had risen to 14%, but barely in Africa. In 2008, for the first time in human history, 50% of the world's population lived in urban areas, with two-thirds of those living in low-income and middle-income nations (Dye, 2008; Jha *et al.*, 2012). Urban population is projected to increase with the highest rate in Africa (UNDESA, 2015). For example, in 2007, the estimated global urbanisation growth rate was 0.8%; at this time, the rate in sub-Saharan Africa was about 1.6%. Urbanisation consumes vast amounts of land in cities and triggers several environmental problems. One notable problem is its negative impact on flooding arising from increased impervious surfaces (Lazaro, 1990; UN-HABITAT, 2005; Dye, 2008; Chen *et al.*, 2009; Suriya and Mudgal, 2012). This suggests greater attention should be paid to the future consequence of urbanisation.

The concept of urbanisation is widely researched and remains a dominant force in urban and urban flooding studies, however, there is still no agreed definition of what the phenomenon is. It has been described as the proportion (or rise in proportion) of total concentrated urban settlements by Davis (1965). More elaborately, it is defined as the concentration of people in urban settlements and the process of change in land-use occupancy, resulting from the conversion of rural lands into urban, suburban and industrial communities (Savini and Kammerer, 1961; Davis, 1965). These definitions clearly suggest urbanisation is concerned with the concentration of human settlement and population as well as the process of change in land-use and conversions. Research has shown that these conversions may result from planned developments (Ren *et al.*, 2003; Xian and Crane, 2005), or from unplanned and uncoordinated developments, termed urban sprawl (Ngoran and Xue, 2015). Flood can result from increased impermeable surface, this means that both the sustainable (planned) and unsustainable (unplanned) forms of urbanisation are both likely to generate unintended effects. In any case, the process of land-use conversions has not been extensively researched for the GPH watershed.

In literature, the concepts of urban growth, urban sprawl and urbanisation have been used interchangeably (Xian and Crane, 2005). Sprawl sometimes refers to unnatural (Sinclair, 1967; Lowry, 1988), unplanned or haphazard growth, (Koenig, 1989; Stanilov, 2004) or undesirable land-use patterns, whether scattered or non-compact (Ewing, 2008). Some other urban-related studies have used the term 'undesirable land-use patterns' (Galster *et al.*, 2001; Irwin and Bockstael, 2002; Theobald, 2005). Urban sprawl may be leapfrogged, scattered, strip, ribbon or continuous low-density developments. From a planning point of view, the desirability of land-use patterns is judged on accessibility, trip length, functional open spaces and so forth which all relate to urban density, land-use (mixes) and time (Ewing, 2008). In contrast, from a hydrological standpoint, many studies have shown that the impact of developments is what render them undesirable or desirable, and not the patterns themselves (Du *et al.*, 2012; Suriya and Mudgal, 2012; Verbeiren *et al.*, 2013). The impact of urbanisation might depend on a combination of factors such as: the size of the basin; the position of the development within the basin; the extent of the urban area; land-use type; basin slope; proximity to flood plain and flood channel; and antecedent moisture content (AMC) as explained earlier.

2.9 SUSTAINABLE DEVELOPMENT AND PLANNING.

Sustainable development is defined in the Brundtland Report as, the development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987:41). In the bid to realise sustainable development, the 'Earth Summit' was held in 1992 which saw 178 countries sign up and set out principles for achieving sustainable development in the United Nations Conference on Environment and Development in Rio de Janeiro, known as the 'Rio Declaration' (UNCED, 1992; Wheeler and Beatley, 2014). In support of the declaration, the Agenda 21 was drafted. This agenda issued action plans for achieving sustainable development in the 21st Century.

In pursuit of the commitments made at Rio, policies have been formulated in many countries (including Nigeria). Results of the Rio commitment in Nigeria include, for example, the National Rolling Plan, the National Housing Policy, the Sanitation Sector Strategy and Action Plan, Vision, 2010 (UN, 1997) and the Rio +20 report (FGN, 2012). In the UK, the land-use planning system remains at the heart of the UK Government's Sustainable Development Strategy (Burton *et al.*, 1996; Defra, 2005). At the city level, local planning authorities are encouraged to pursue sustainable development using precautionary approaches, for example, by directing developments to existing urban areas and Brownfield, rather than Greenfield and suburban areas. Moreover, United Nations member states were encouraged to use environmental assessment as an integral part of the development process (UNCED, 1992). To date, formal legislation, or at least guidelines, have been produced in many developing countries. However, the main obstacle remains adequate implementation of sustainable development in the region (Wood, 2003; Alshuwaikhat, 2005; UNECA, 2011; Ingelson and Nwapi, 2014; Wheeler and Beatley, 2014).

In planning, several attempts and contributions have been made to promote the concept of sustainable development. One goal is to achieve the most sustainable urban form during planning (Burton *et al.*, 1996; Thomas and Cousins, 1996; Williams *et al.*, 1996). In this regard, the idea of building a 'compact city' or urban intensification remains central in much of the literature (Williams *et al.*, 1996). At the same time, this was a contentious idea (Burton *et al.*, 1996; Thomas and Cousins, 1996; Biddoccu *et al.*, 2016). Recent studies argue that the desirability of compactness is not rooted in sustainability imperatives such as flooding, air quality, water quality and so forth but rather on their trade-offs such as transport; conservation of fossil fuel energy; waste minimisation e.g. carbon emissions (Burgess and Jenks, 2002). These priorities underscore why fast growing cities may overlook the impacts of flooding.

There is also considerable debate over the preferred spatial model of a compact cities and the degree of compactness (Burton *et al.*, 1996; Williams *et al.*, 1996; Williams *et al.*, 2000). Williams *et al.* (2000) argued that there is no single sustainable urban form, but rather, a variety of forms which depend on the physical nature of the area and strategic objectives of the planning authorities, which is consistent with the view in hydrologic studies (Jones, 2000b; Parker, 2000a). For example, according to Heggen *et al.* (1996) and Jones (2000b), the impact of an urban development depends on many factors, including the size of the river basin, location and size of the development, land-cover and other physiographic factors.

Impervious surface from urbanisation has become a central issue in urban hydrology. It is often used as an indicator of intensity in urban planning and flood prevention because of its impact on hydrology (Carlson and Traci Arthur, 2000; Brabec *et al.*, 2002; Niehoff *et al.*, 2002; Oni *et al.*, 2015). As stated earlier, increased impervious surfaces (that is, the proportion of a catchment covered by surfaces due to the erection of roads, roofs, and parking lots and so on) and hydraulically inefficient drainage systems in urban areas result in increased flood magnitude and frequency. Impervious surfaces also cause decreased infiltration capacity, groundwater levels and water quality, decreased lag time, increased stream channel and bank erosion and so forth (Carlson and Traci Arthur, 2000; Sung *et al.*, 2013; Miller *et al.*, 2014).

Still on to the idea of 'compactness', studies in hydrology have indicated that compact or high-density developments are more likely to cause significant impact on flooding locally. Pauleit and Duhme (2000) found that that the maximum runoff was expected in compact and very densely built-up areas such as multi-storey factories and housing. Increased runoff is due to the higher proportion of impervious land-cover in the area. However, this work only looked at the environmental impacts of sub-units, i.e. housing schemes, commercial and industrial developments and services. It did not consider the impacts of location alternative to the developments within sub-catchments. This raises an important question in this study area: *what alternative location is least disruptive in relation to flooding in the Greater Port-Harcourt Watershed?* This is important for understanding the effect of the position of developments on runoff.

2.9.1 Environmental Impact Assessment.

Environmental impact assessment (EIA) is a systematic process of identifying, predicting, evaluating, and mitigating the biophysical, social, and other relevant effects of proposed projects and physical activities prior to major decisions and commitments being made (Sadler, 1996). EIA first formalised in the US National Environmental Policy Act (NEPA, 1969) was later developed in the Council on Environmental Quality, CEQ (1978). Since then, the adoption of environmental assessment has been widespread and exists in a number of specific forms that are outside the scope of this study (Morgan, 2012; Glasson *et al.*, 2013).

The other forms include strategic environmental assessment (SEA), sustainability assessment (SA), social impact assessment (SIA), health impact assessment (HIA) (Glasson *et al.*, 2005). For example, like EIA, SEA is a systematic process for identifying and evaluating potential impacts, in contrast SEA is used for higher level decision-making such as policies, plans and programmes (PPPs) (Dalal-Clayton and Sadler, 1999; Partidario and Clark, 2000; Fischer, 2003; Abaza *et al.*, 2004; Alshuwaikhat, 2005; Retief, 2007; Tetlow and Hanusch, 2012).

Generally, the EIA process is not uniform from country to country. The process differs slighlty in published work, for example in Lawrence, (2003) and Glasson *et al.* (2013). However, it consists of a set of procedural steps which includes a written environmental impact statement (EIS) report to inform decision-makers. In Glasson *et al.*, (2013) it includes: Identifying and Defining the Project or Activity, Scoping, Preparation of terms of reference, Preparation of Draft EIA, Public participation, Preparation of final EIA, Decision making, Administrative or Judicial review, and Project Implementation and Monitoring.

Globally, EIA has been recognised as a key instrument for managing and regulating planned projects (Glasson and Salvador, 2000; Morgan, 2012). Studies show that EIA is now widely adopted in several jurisdictions (Sadler, 1996; Wood, 2003; UNECA, 2005; Morgan, 2012; Glasson *et al.*, 2013). Since its enactment in the United States, there has been widespread adoption of the process which started in more developed countries and later used in developing countries (Glasson *et al.*, 2005). Today, at least 140 countries have EIA systems (Glasson *et al.*, 2013). However, there are differences in the way there are enforced. EIA in some jurisdictions is enforced through acts of status, in others through mandatory regulation. In some other cases only EIA guidelines are used (Wood, 2003; Glasson *et al.*, 2013). In Europe, approval of the European EIA Directive (85/337/EEC) stimulated uptake in several European countries (Glasson *et al.*, 2005). In Africa, a large number of EIA regulations and guideline were established in 1990s, while in Nigeria, EIA decree was first enacted in 1992.

A plethora of studies have made several contributions e.g. (Canter, 1996; Sadler, 1996; A, 2001; Steinemann, 2001; Cooper and Sheate, 2002; Wood, 2003; Sandham and Pretorius, 2008; Morgan, 2012; Glasson *et al.*, 2013; Kolhoff *et al.*, 2016). Two aspects often emphasised are the role and purpose of EIA (Sadler, 1996; Ridgway, 1999; Che *et al.*, 2011; Glasson *et al.*, 2013). According to Sadler (1996) and Glasson *et al.* (2013), EIA has a role to aid decision-making. It also has a role to aid the formulation of development actions in planning and to aid the achievement of sustainable development. About urban planning, Che *et al.* (2011) maintained that a key aim of EIA is to strengthen the capacity to incorporate environmental concerns into planning and project implementation. Generally, a large number of studies agree that EIA is an important regulatory instrument that help make urban planning more environmental-friendly. However, EIA if poorly implemented may have negative consequences on the environment (Glasson *et al.*, 2005). One key area in EIA practice that often demand attension is the consideration of alternatives (Morgan, 2012). Consideration of alternatives help inform decision makers on locations that are less disruptive (Sánchez and Hacking, 2002).

2.9.2 Alternatives in Environmental Impact Assessment and Planning

Alternatives are options, choices, or courses of action considered for meeting goals (Steinemann, 2001). The consideration of alternatives is among the important stages in planning and the environmental assessment processes (Sadler, 1996; DEAT, 2004; Glasson *et al.*, 2005; Diller, 2016). With a goal to make a rational selection of the 'best option'. It involves the evaluation of a range of options for meeting the objectives of the project plan (Steinemann, 2001; González *et al.*, 2015). Broadly speaking it helps in providing a framework for good decision-making based on sustainable development principles (DEAT, 2004). According to Steinemann (2001), the quality of decision-making depends on the quality of available alternatives from which to decide on. Alternatives are regarded as the heart of environmental impact assessment (CEQ, 1978).

In EIA, alternatives can be analysed after scoping (Lawrence, 2003) (See Appendix 2.3). The process involves the consideration of a range of options e.g. locations, approaches or designs. Note: alternatives are also considered in SEA for strategic level decision making (Therivel and Paridario, 2013). Generally, according to Sadler (1996), the consideration of alternatives to an action is key to creative, pre-emptive and decision-relevant assessment. However, the ODPM & WAG (2012) has emphasised it is not the purpose of the environmental assessment process to decide the alternative to be chosen for the action, rather decision-makers are responsible for making a choice to be adopted. The development and comparison of alternatives enable the decision-maker to determine which the best option is (João, 2005). Glasson *et al.* (2013) stated that different alternatives are likely to generate different degree of impact. This implies that an environmentally-friendly option also depend on the quality of decision-making. In the context of urban hydrology, it suggests that poor decision-making e.g. wrong or biased selection of alternatives can affect the magnitude and frequency of flooding in a hydrologically sensitive basin.

Both at project and strategic levels, the consideration of alternatives remain central or a core feature in promoting environmental assessment (Glasson *et al.*, 2005; Therivel and Paridario, 2013; González *et al.*, 2015; Kim *et al.*, 2015). Alternatives are required under national, international law, and international agreements e.g. National-the Nigerian EIA Decree, (FGN, 1992) and the Scottish EIA Regulation (The Scottish Government, 2011); international law-the SEA Directive 2001/42/EC (EC, 2001); international agreement-the Kiev Protocol (UNECE, 2003).

To date, several studies have advanced the concept of alternative e.g. (Steinemann, 2001; Theobald and Hobbs, 2002; Glasson *et al.*, 2005; João, 2005; Glasson *et al.*, 2013; Therivel and Paridario, 2013; Scannapieco *et al.*, 2014; González *et al.*, 2015; Kim *et al.*, 2015; Nicolaisen and Næss, 2015). Several aspects of alternative consideration have been deliberated in studies including benefits, types of alternatives as shown in Glasson *et al.* (2005). The process for developing alternatives as shown in Figure 2.11b. The processes as summarised in González *et al.* (2015), involves: identification and development, assessment and comparison, selection and documentation. In hydrology, location alternative can be important because the placement of impermeable surfaces due to developments can influence runoff in catchments (Mejía and Moglen, 2009; Su *et al.*, 2014; Du *et al.*, 2015). One aspect not often found in studies is the effect of different alternatives on urban hydrology. To the best of the author's knowledge, published work on the effects of location alternative on urban hydrology is very rare.

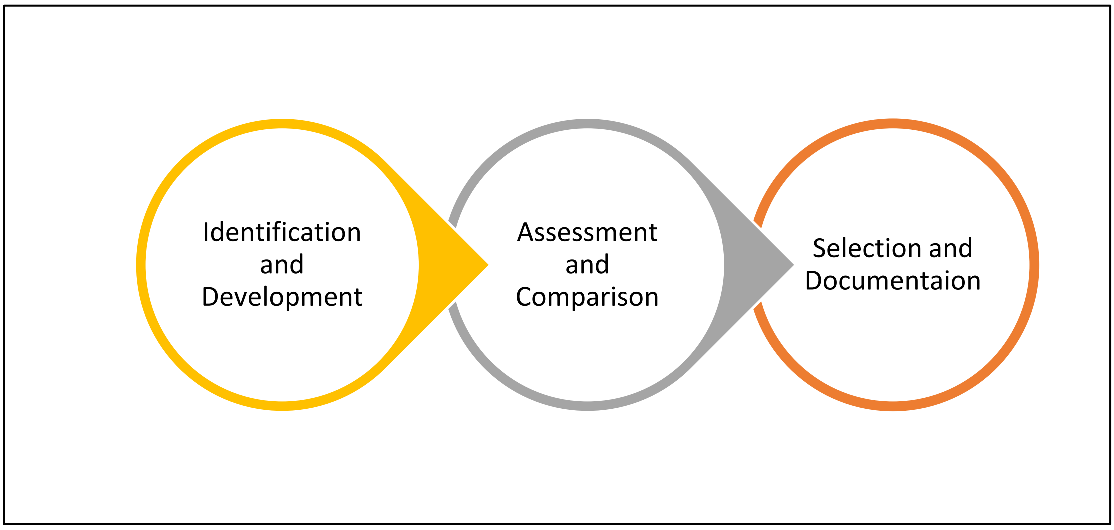


Figure 2.11b Illustrates the key processes involved in choosing alternatives which involves identification and development, assessment and comparison, selection and documentation. (González et al., 2015).

2.10 ENVIRONMENTAL ASSESSMENT IN GREATER PORT-HARCOURT

2.10.1 Brief Description of the Regulatory and Administrative Framework of Environmental Assessment in Nigeria.

EIA has become a formal process and requisite practice for permitting planned projects in Nigeria. The EIA systems used for regulating infrastructural developments can be framed into three systems with distinct legislation and regulators (see Figure 2.12). They include:

(1) The Petroleum Act of 1969 accompanied by the Environmental Guidelines and Standards (EGAS) is used to control developments in the oil and gas sectors and are regulated by the Directorate of Petroleum Resources (DPR), (FGN, 1969; DPR, 1999, 2002). The Petroleum Act which focuses on petroleum matters is not directly an EIA legislation, but makes provision in section 9, subsection (10) (b) (iii) for the Minister to make a future environmental regulation about petroleum projects which includes the EGAS (FGN, 1969).

(2) The EIA Decree 86 of 1992 is the principal legislation covering all sectors (FGN, 1992a); The Decree 86, formerly enforced by the Federal Environmental Protection Agency (FEPA), is in 2017 regulated by the National Environmental Standards and Regulations Enforcement Agency (NESREA) which is an agency under the Federal Ministry of Environment (FMEnv).

(3) The Town and Country Planning (TCP) Decree 88 of 1992 covers town, urban and regional planning and is regulated by the Ministry of Land and Housing in various states and local governments (FGN, 1992b).

In any case, these legislations share a common goal, to promote environmental friendly developments in the country by integrating environmental concerns into proposed projects in Nigeria (FGN, 1992b, a; DPR, 2002).

Box 2.4 Relevance for study

Urbanisation is considered a non-climatic driver of flood risk in this study. In this study, I considered that urban expansion or urbanisation can occur by means of unplanned and planned developments. While unplanned developments result from urban sprawl, major planned developments are often regulated using the EIA process. The consideration of alternatives are considered a core feature of the EA processes. In this study, the effects of location alternative were considered because the placement of impermeable surfaces can affect runoff in subbasins.

Administratively, NESREA has the lead role and the responsibility to regulate all sectors (including petroleum, as well as urban & regional planning) on behalf of the Federal Ministry of Environment in Nigeria (FMEnv). Other authorities, such as the DPR and the Ministry of Urban and Regional Planning ideally have a supporting role in regulating specific sectors (petroleum and urban & regional planning respectively) as shown in Figure 2.12. According to the 2007 NESREA Act, "NESREA has the responsibility for the protection and development of the environment, biodiversity conservation and sustainable development of Nigeria's natural resources in general and environmental technology, including coordination and liaison with relevant stakeholders within and outside Nigeria on matters of enforcement of environmental standards, regulations, rules, laws, policies and guidelines," (FGN, 2007:'no page'). Its enforcement functions involve ensuring compliance with EIA laws, guidelines, policies and standards of other environmental regulation in the country.

Ideally, environmental assessment should adequately evaluate the potential impacts (positive or negative) of projects and their alternatives to help decision makers determine the most sustainable option (Fernandes, 2000; Steinemann, 2001). However, this is not always the case in Nigeria. The effectiveness of the EIA process have been criticised in recent years as stated in Adomokai and Sheate (2004); Ogunba (2004); Isah (2012) and Ingelson and Nwapi (2014). One reason is that of the execution of key aspects of the process. For example, the examination of alternatives significantly falls short of best practice. The key issues will be summarised in a later paragraph.

Despite the drawbacks, the Decree 86 recognised as the main EIA legislation has three key objectives and 13 principles, found in Appendix 2.4 (FGN, 1992a). The objectives are:

a) To establish prior consideration of activities likely to have a significant impact on the environment before projects are undertaken by any person, corporate body or the government are authorised.

b) To promote the implementation of appropriate policy at federal, state and local government level to meet objective (a).

c) To encourage the advancement of information exchange, notification and consultation when proposed activities are likely to generate significant environmental trans-boundary, or trans-state, effects.

Among other principles (see Appendix 2.4), paragraph 4 (d), of Decree 86, states that, as a minimum, EIA should include, "An assessment of the likely, or potential, environmental impacts of the proposed activity and the alternatives, including the direct or indirect,

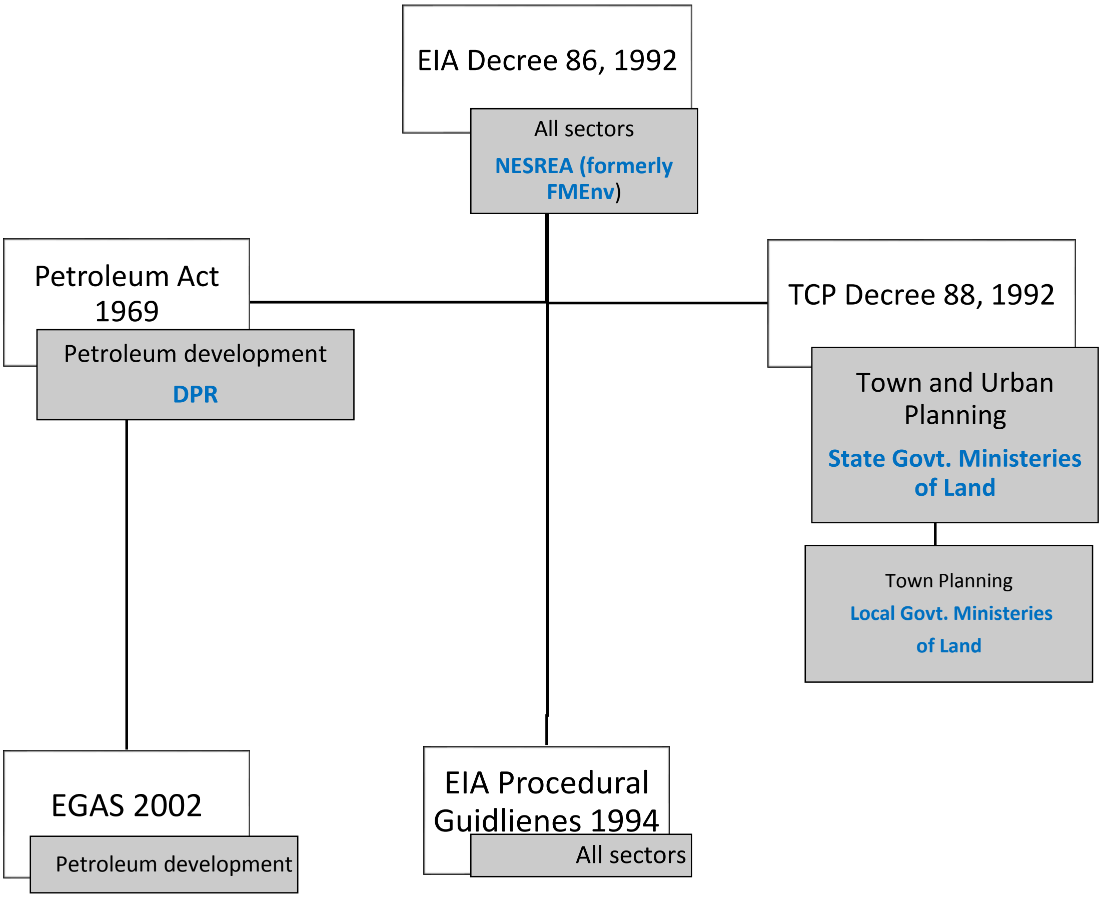


Figure 2.12 Administrative and legal framework of EIA in Nigeria. The blue coloured letters specify the administrative. Black coloured letters specify the legal framework.

cumulative, short-term and long-term effects,"(FGN, 1992a: 'no page'). A list of categories and mandatory projects requiring EIA are stated of which infrastructural projects are included (See Appendix 2.5 and 2.6 for details). Procedurally, the entire process involves the submission of the project proposal, screening of projects based on project category, scoping, drafting of the initial EIS report, public hearing and panel review, drafting of the final EIS report, decision-making, monitoring and auditing, as illustrated in Figure 2.12.

Ideally, on receiving the screening report, the FEPA (1994) guideline emphasises the need for the proponent to conduct a scoping exercise. To also ensure that all significant impacts and reasonable alternatives are adequately addressed in the EIA. This shows the level of importance attached to the consideration of alternatives in the legislation. In reality, the environmental assessment process is considered ineffective (Ogunba, 2004; Nwoko, 2013). Nwoko (2013) stated that the entire scoping and EIA process rarely meet objectives.

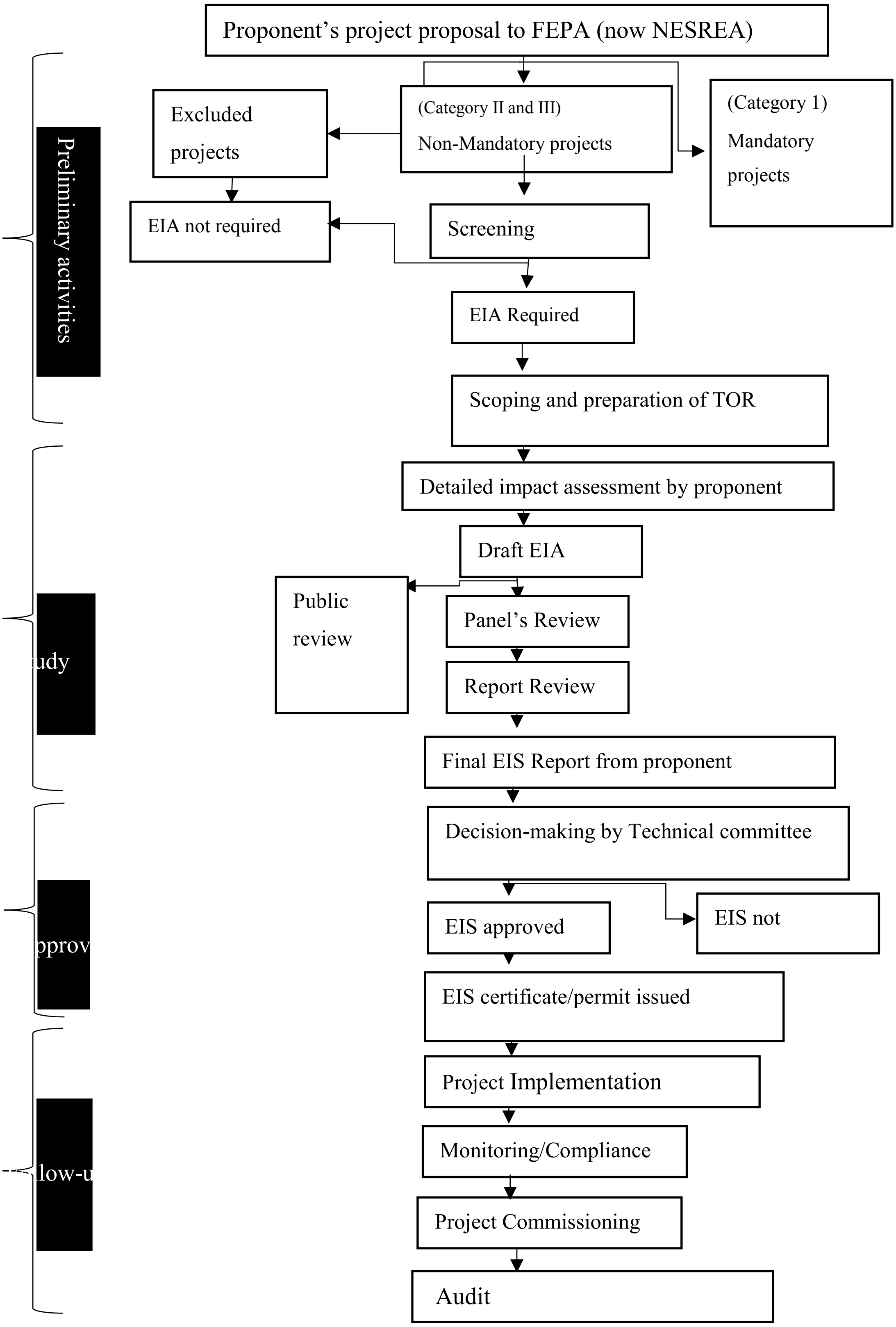


Figure 2.12 The Nigerian EIA Process in the EIA Decree 86. Three main stages comprise of the preliminary activities, EIA study, appraisal and follow-up. Source: FEPA (1994).

EIA as a project planning tool is designed to contribute to achieving sustainable development in Nigeria. A good number of studies have critically evaluated advances in Nigeria's EIA practice (Olukesusi, 1992; Olokesusi, 1995, 1998; Akpofure and Echefu, 2001; Anago, 2002; Zagi, 2002; Adomokai and Sheate, 2004; Ogunba, 2004; Yusuf *et al.*, 2007; Isah, 2012; Nwoko, 2013; Ingelson and Nwapi, 2014). Few studies have acknowledged the progress made in terms of the increased number of projects subject to EIA, where progress was attributed to democratisation and economic growth in Nigeria (Nwoko, 2013; Ingelson and Nwapi, 2014). However, the majority of early and later studies agree that the EIA process in Nigeria is ineffective, fraught with shortcomings and rarely meet objective (Olukesusi, 1992; Olokesusi, 1995, 1998; Akpofure and Echefu, 2001; Anago, 2002; Zagi, 2002; Adomokai and Sheate, 2004; Ogunba, 2004; Yusuf *et al.*, 2007; Isah, 2012; Nwoko, 2013; Ingelson and Nwapi, 2014). The key issue is underscored in the next paragraph, hence, only issues related to the consideration of alternatives were elaborated upon.

For example, Ingelson and Nwapi (2014:5) argued that EIA practice in Nigeria reflects "Tokenism with no meaningful achievement." Anago (2002:11) added that although the process is backed by a "world class" EIA legislation, it often fails at the implementation stage. Olokesusi (1998), Ogunba (2004), Yusuf *et al.* (2007), Isah (2012), Nwoko (2013), Ingelson and Nwapi (2014) showed that the shortcomings range from lack of coordination among agencies, lack of workforce (capacity) and facilities to lack of adequate scoping, and monitoring. Furthermore, the unavailability of baseline data, inadequate mitigation measures, multiplicity of function, lack of substantial public participation especially in rural areas, and limited scope of EIA review are also serious issues highlighted in the above studies.

In terms of a multiplicity of functions, the EIA system has been criticised for regulating oil and gas related projects under two systems: the Decree 86 by NESREA and the Petroleum Act 1969 DPR, respectively (Ogunba, 2004; Isah, 2012; Ingelson and Nwapi, 2014). Regarding alternatives, Nwoko (2013) argued that the identification and examination of alternatives in the EIA system are infrequent. As stated above, the EIA Decree 86 and the FEPA guideline requires the identification and examination of alternatives to the project (FGN, 1992a; FEPA, 1994), but in reality, they are rare and are poorly done with limited scope (Ogunba, 2004).

2.11 CONCEPTUAL FRAMEWORK AND DEVELOPMENT OF RESEARCH QUESTIONS

This section presents the conceptual framework that connects the main concepts being studied (Figure 2.13). The framework was based on an adaptation of the Ice (2002) and Schanze (2006) source-pathway-receptor-consequences (SPRC) conceptual model. This SPRC risk model provides a reference point and situates this study within the different knowledge bases. Relevant concepts in Ice (2002), Schanze (2006), Davis (1965), Leopold (1968), Hollis (1975), Brooks (1985), Lazaro (1990), Jones (2000b), Glasson *et al.*, 2005, White and Greer (2006), Ewing (2008), Wheater and Evans (2009), Jha *et al.*, (2012);), formed the conceptual foundation for this study.

The source-pathway-receptor-consequences in Schanze (2006) is a simple causal chain used to explain the interaction between physical processes (causes) and their consequences (effects). This ranges from causes such as rainfall (a direct driver) and land-use changes resulting from urbanisation at the source to effects on runoff (measured by peak discharge) and effects on flood hazards in the pathway. The causal chain ideally continues further to effects on receptors (i.e. elements at risk) and consequences, which is a matter of societal value (Schanze, 2006). While climatic factors such as rainfall cannot be controlled, land-use changes resulting from urbanisation can be managed. Hence, runoff and inundation in flood risk pathways can be influenced by appropriate management (Ice, 2002).

Receptors or elements at risk comprises of people, infrastructure, property and the environment, whereas the negative consequences include for example, pollution, economic damage and loss of life. The receptor refer to the vulnerability of elements at risk, whereas consequences stand for harm to values (Schanze, 2006). According to Ice (2002), the management of flooding is profoundly biased towards the receptor end of the flood risk chain because the greatest control can be exerted there. Conversely, preventive management of risks, impacts on hazards (at the source end of the chain) are often preferred as early as possible (Merz *et al*., 2007; Jha *et al*., 2012). Therefore the goal of this study goal is mainly to investigate changes at the source-pathway end of the flood risk chain. This study focuses on changes in land-use at the source and the effects on flooding in pathways (Figure 2.13). Moreover, the damage potential of the hazards and the elements at risk were identified by means of their exposure to high damaging floods. In this study, priority areas, elements at risk including land uses, important infrastructure, roads, and rails were identified.

In terms of cause-effect relationship in this study, all actions or events at the source end of the model are considered causes, whereas changes and impacts in the pathway onwards are considered effects. Heggen et al. (1996), Jones (2000b), Wheater and Evans (2009) have suggested that flooding is caused by the interactions between climatic (rainfall) and non-climatic factors (land-use changes) due to human modifications resulting from urbanisation. While rainfall is uncontrollable, urbanisation has scope for management (Jones, 2000a), which gave the impetus for this study. Urbanisation refers to the concentration of human settlement and population as well as the process of change in land-use and conversions (Davis, 1965) and is recognised as the most dramatic of all land-use changes in terms of its effects on flooding (Leopold, 1968; Hollis, 1975; Lazaro, 1990; Booth, 1991). Like in Port-Harcourt, urbanisation in mega cities of most developing regions result from unplanned and planned developments (Ewing, 2008; Jha *et al*., 2012). The planned expansion of Greater Port-Harcourt involves the conurbation of the Old City and surrounding communities (GPHCDA, 2010; Owei *et al*., 2010), see more details in chapter 3.

Unplanned and scattered developments are often referred to as 'urban sprawl' which can occur in several forms or archetypes (Ewing, 2008). From a planning standpoint, these are often non-compact archetypes of development which are usually considered undesirable (Williams *et al*., 2000). They include continuous low-density, leapfrog, ribbon, scattered developments and so forth (Ewing, 2008). Paradoxically, planned developments can also generate unintended effects. Among other factors, impacts can result from weak implementation of regulations (Sung *et al*., 2013) and poor choice of alternatives in the developmental planning process (Sadler, 1996; Steinemann, 2001). Sadler (1996) and Glasson *et al*. (2013), suggest that different alternatives are likely to generate different effects. This then raise some questions such as: *What are the historic and future changes in the LULC of Greater Port-Harcourt Watershed?* Secondly, *what are the impacts of the hypothetical alternatives to Phase-1 projects (derived from the official Masterplan in the GPH watershed) on flooding?*

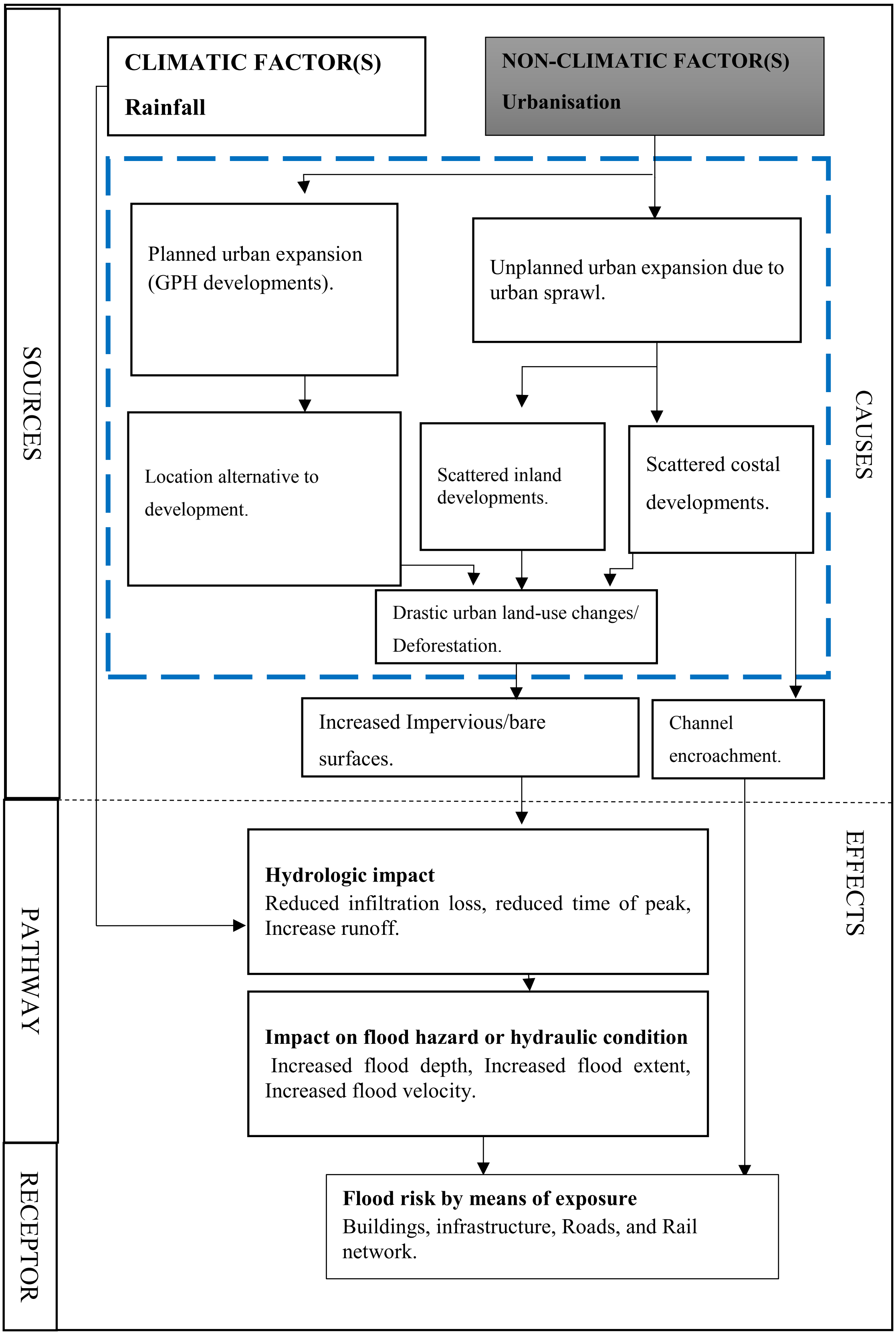


Figure 2.13 The conceptual framework of the study.

Urbanisation pressure from planned and unplanned developments is likely to generate significant impacts on flooding due to urban land-use changes and deforestation that often result in increased percentage of impervious surface and decreased interception loss (Lazaro, 1990; White and Greer, 2006). Moreover, in the coast, urbanisation may also increase flood risk due to urban sprawling which often result from increased channel encroachment (Ngoran and Xue, 2015).

The net effects of land-use changes are increased flood magnitude and frequency (Booth, 1991; Heggen *et al.*, 1996; Parker, 2000). Urban land-use change starts off by altering runoff and discharge into river channels, measured by peak discharge and runoff volume. Urbanisation may also make subbasins flashier which is measured by lag time. Discharge into river channels affect the magnitude of flood hazard (measured by changes in flood depth, flood velocity and flood extent) (Schanze, 2006). Hence, these parameters were used to assess the effects of urbanisation and climate change on flooding in the studied area. It also raises the question: *What are the effects of land-use changes on flooding in the GPH watershed based on historical urbanisation and the proposed masterplan?*

Moreover, research has shown that decrease in vegetal cover leads to decreased interception loss as well as increased runoff, depending on the size of the basin (Brooks, 1985). Considering the size of the GPH watershed, it raises another question: *To what extent could afforestation in the GPH watershed reduce flooding?* Lastly, considering future flood risk management in the Greater Port-Harcourt area, the final research question is: *How can the Greater Port-Harcourt Development Authority improve future planning using new insights into flood risk?*

Chapter 3. Description of Study & Project Area.

3.1 INTRODUCTION.

This chapter presents the description of the study area and the Greater Port-Harcourt City Development in River State, Nigeria. Firstly, the study area described covers the geographic, demographic and biophysical setting of the environment in sections 3.2, 3.3 and 3.4 respectively. Description of the watershed was done in section 3.5. Section 3.6 describes the GPH Masterplan and project starting with the background, Phase-1 project justification, environmental sustainability and lastly the GPH project alternatives.

3.2 THE GEOGRAPHIC SETTING.

3.2.1 The Niger Delta.

Geographically, the Niger Delta region covering Port-Harcourt in River State is situated in the southernmost part of Nigeria in West Africa (see Figures 3.1 and 3.2). By definition, the Niger Delta is a coastal region with distinctive geography demarcated by a natural delta of the River Niger system (Reijers et al., 1997; NDDC, 2006). It is located in the Gulf of Guinea between longitude 5ºE to 8ºE and latitudes 4ºN to 6ºN, bordered by the Atlantic Ocean on the south; Cameroon on the east; Lagos State on the west and Onitsha on the north (Tuttle et al.; Abam, 1999; Adekola and Mitchell, 2011). The extensive wetland delta is considered the largest in the African continent and the third largest in the world (Abam, 2001; Chiadikobi et al., 2011). As shown in Table 3.1, the entire Niger Delta covers an area of 94,947 km^2, i.e. about 10% of the Nigerian land mass (NDDC, 2006). Hence, its southern coastline frames the continental margin of the Gulf of Guinea, spanning 450 km (Reijers et al., 1997).

Globally, river deltas e.g. the Huanghe Delta, Liaohe Delta and Niger Delta, are among the most densely populated areas of the world perhaps due to the various benefits they provide for humans such as: flat topography, fertile soils for agriculture, access to harbours for export and trade, access to marine and water resources, extensive biodiversity in addition to subsurface oil and gas deposits (Liu et al., 2000; IADC, 2009; Kuenzer et al., 2014). The Niger Delta region presently host over 30 million inhabitants making up about 20% of the Nigerian population that is attracted to the region (Kuenzer et al., 2014). Hence, the combination of its geography, topography and abundant natural resources, in addition to oil and gas resources, makes it an area of global and regional importance. Nevertheless, a gamut of studies have also demonstrated that the region is very vulnerable to the impact of natural and anthropogenic hazard due to several natural and socio-economic factors (Abam, 1999; Abam, 2001; Ologunorisa 2004; NDDC, 2006; Kuenzer *et al.*, 2014).

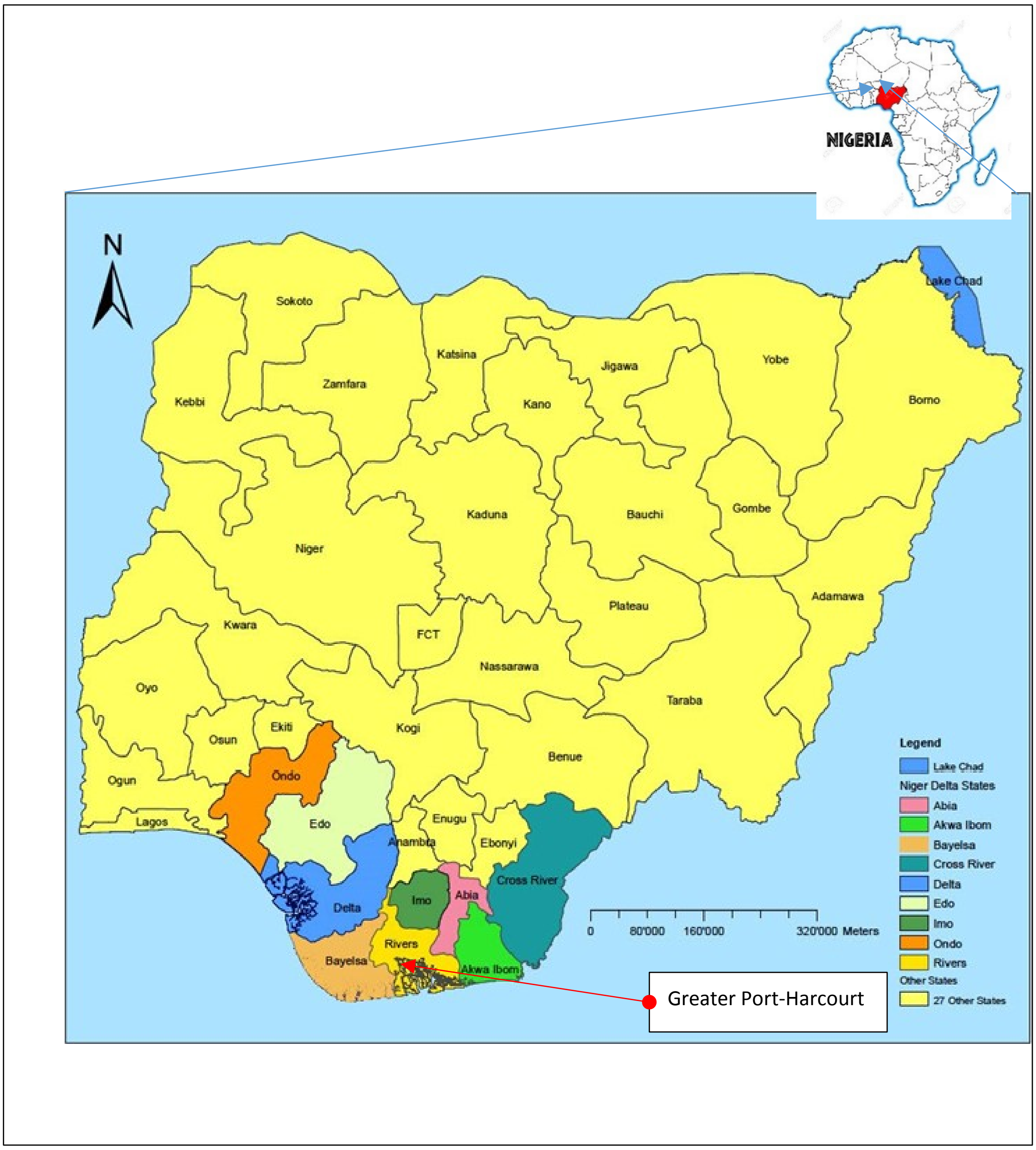


Figure 3.1 Geographical location of Port-Harcourt and the Niger Delta states in Nigeria. On the map Port-Harcourt is bounded on the west by Bayelsa state, on the east by Abia and Cross River and on the north by Imo state (Source: Ite *et al.* (2013).

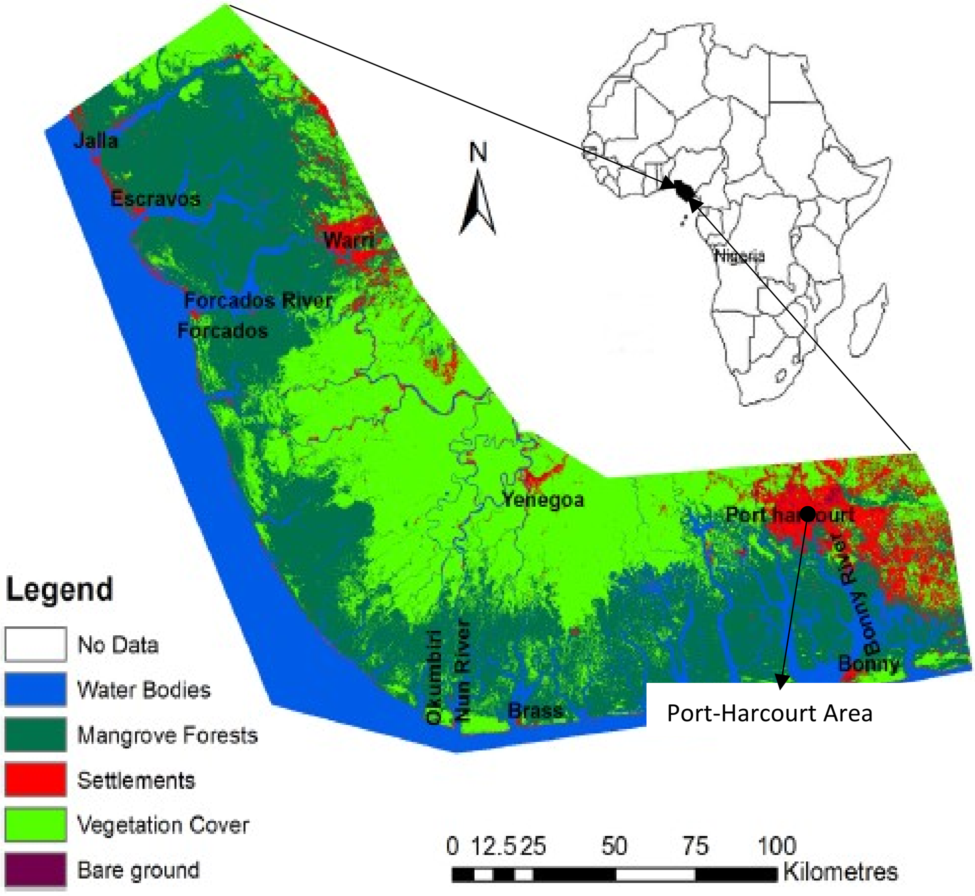


Figure 3.2 Coastal and Land-cover map of the Niger Delta region covering Port-Harcourt. It indicates urbanisation is greater around the Port-Harcourt area (Musa *et al.*, 2014).

great environmental functions including habitat provision, climate stabilisation, pollution purification and flood protection. On the other hand, the IADC (2009) has argued that deltas are often subject to environmental impacts, e.g. flooding and as such require frequent attention. Recent observers have criticised the way in which economic developments are carried out in the environmentally sensitive Niger Delta. Development practices in the region are often viewed as unsustainable due to accelerated environmental degradation coupled with inadequate consideration for the environment during planning (Abam, 1999; Ologunorisa 2004; Uyigue and Agho, 2007; Allen, 2010; UNEP, 2011; Bariweni *et al.*, 2012; Enaruvbe and Ige-Olumide, 2014; Kuenzer *et al.*, 2014).

3.2.2 Port-Harcourt City.

Port-Harcourt is the administrative capital of Rivers State and the largest city in the Niger Delta with a population exceeding one million inhabitants (NDDC, 2006). It lies approximately 20 km inland of the Bonny River and is located at 4˚42 north and 4˚47 north latitude as well as 6˚55 east, 7˚08 east longitude in the equatorial region of the world. South of the city is a peninsula protruding out into the mangrove swamps along the Bonny River (Theis et al., 2009), while north of the city is fringed with rainforest that extends into Imo State. The city is a metropolitan area situated on the eastern flank of the Niger Delta and occupies an area of about 360 km^2 (NDDC, 2006; Ikechukwu, 2015). Geopolitically, Port-Harcourt is located in the south-south region of Nigeria and is the fourth largest city in Nigeria after Lagos, Kano and Ibadan (Ede et al., 2011). It consists of a low-lying coastal plain that is barely 20 m above sea level. It has a relatively flat terrain with a slope not greater than 3% (Ikechukwu, 2015). South of the city is also characterised by low-level mud flats, while north of the city is chracyerised by higher elevation terrain.

The old city was a port city, established in 1913 during the British colonial rule and was named after Lord Lewis Harcourt, the then Secretary of State for Colonies (Owei et al., 2010; Ede et al., 2011). Due to its geographical location (near the coast), the city was established as a rail and seaport terminal for the exportation of coal and agricultural produce from the north (Wolpe, 1974; Ikechukwu, 2015). Like so many new cities, the discovery of oil and gas accelerated the industrial and commercial expansion. And by 1965 the municipality became the site of Nigeria's largest harbour and the centre of Nigeria's petroleum activities (Wolpe, 1974; Izeogu, 1989). Since then, there has been a constant influx of people into the city. Apart from the rise in population, the city has been expanding physically (see section 3.3). Up until now, the city's planning authority have struggled to cope with the expansion. Studies theorise that the economic activities in the city led to high influx and overcrowding, accompanied by uncontrollable urban sprawl (ERML, 2009; Theis et al., 2009). Other studies added that the existing infrastructure is in a deplorable condition and has been overburdened (Owei et al., 2010; Ede et al., 2011). Ede *et al*., (2011) noted that the high population densities (see Figure 3.8), congestion, un-serviced areas and decaying utilities contrast sharply with the Government's original vision.

3.2.3 Greater Port-Harcourt Area.

Greater Port-Harcourt (GPH) includes the Port-Harcourt City and the surrounding areas laid out for urban redevelopment, expansion and modernization. It is an agglomeration or conurbation of the old Port-Harcourt City and parts of other Local Government Areas (LGAs) defined in the Greater Port-Harcourt City Masterplan. Geopolitically, the eight LGAs include Port-Harcourt, Obio-Apko, Okrika, Oyigbo, Ogu-Bolo, Etche, Eleme and Ikwerre (See Figures 3.3-3.6). Port-Harcourt LGA is in the middle, Bonny LGA is located in southernmost part; Oyigbo, Eleme and Okrika Ogu-Bolo LGAs are located in the east and south of the Central Business District. Obio/Akpor is situated north of Port-Harcourt LGA; Ikwerre LGA is situated north-west of Obio/Akpor LGA, while Etche LGA is in the north-east.

Geographically, Port-Harcourt city was originally made up of three LGAs that is: Port-Harcourt, Obio-Akpo and Okrika LGAs. Hence, in the urban plan, GPH now includes Ikwerre, Oyigbo, Ogu/Bolo, Etche, and Eleme (GPHCDA, 2010). The area of the entire River State is about 10,400 km^2 (Figure 3.4), and the GPH area span 1900 km^2 (Figure 3.5), however, the actual Masterplan area is about 632.5 km^2 (Figure 3.6). Importantly, the watershed delineated for study span about 4821 km^2. Figure 3.3, 3.4 and 3.5 shows the administrative boundaries of the GPH area, while Figure 3.6 shows the actual location of Phase-1 layout and the entire Masterplan within the administrative boundaries. It shows that the Masterplan sits in the middle of the administrative boundaries, while Phase-1 project is located in the northern axis of the Masterplan.

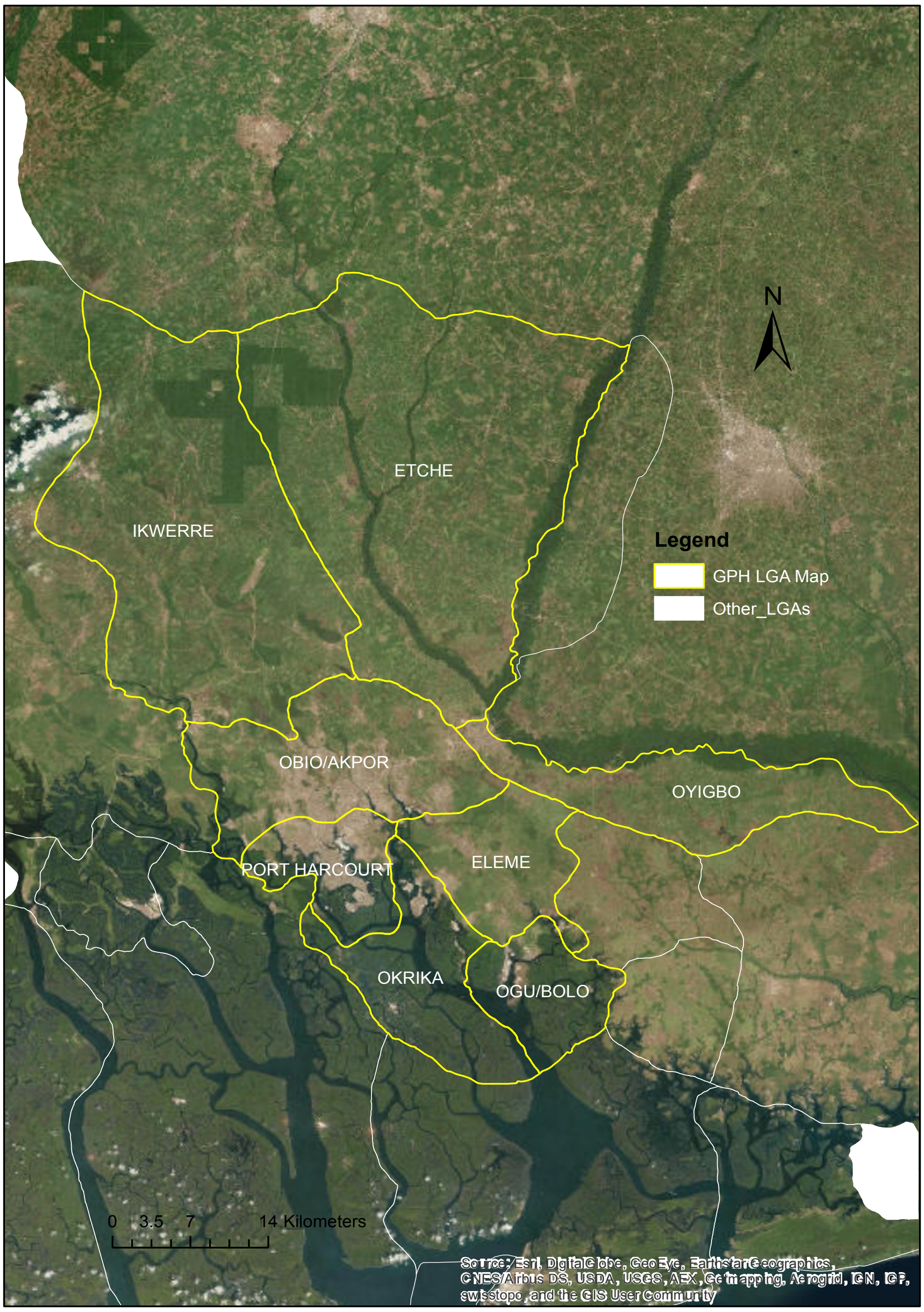


Figure 3.3 Year 2013 base map and year 2001 administrative boundaries map of local government areas that make- up Greater Port-Harcourt. Source: ESR1 (2015)/Rivers State Ministry of Land and Housing (1995).

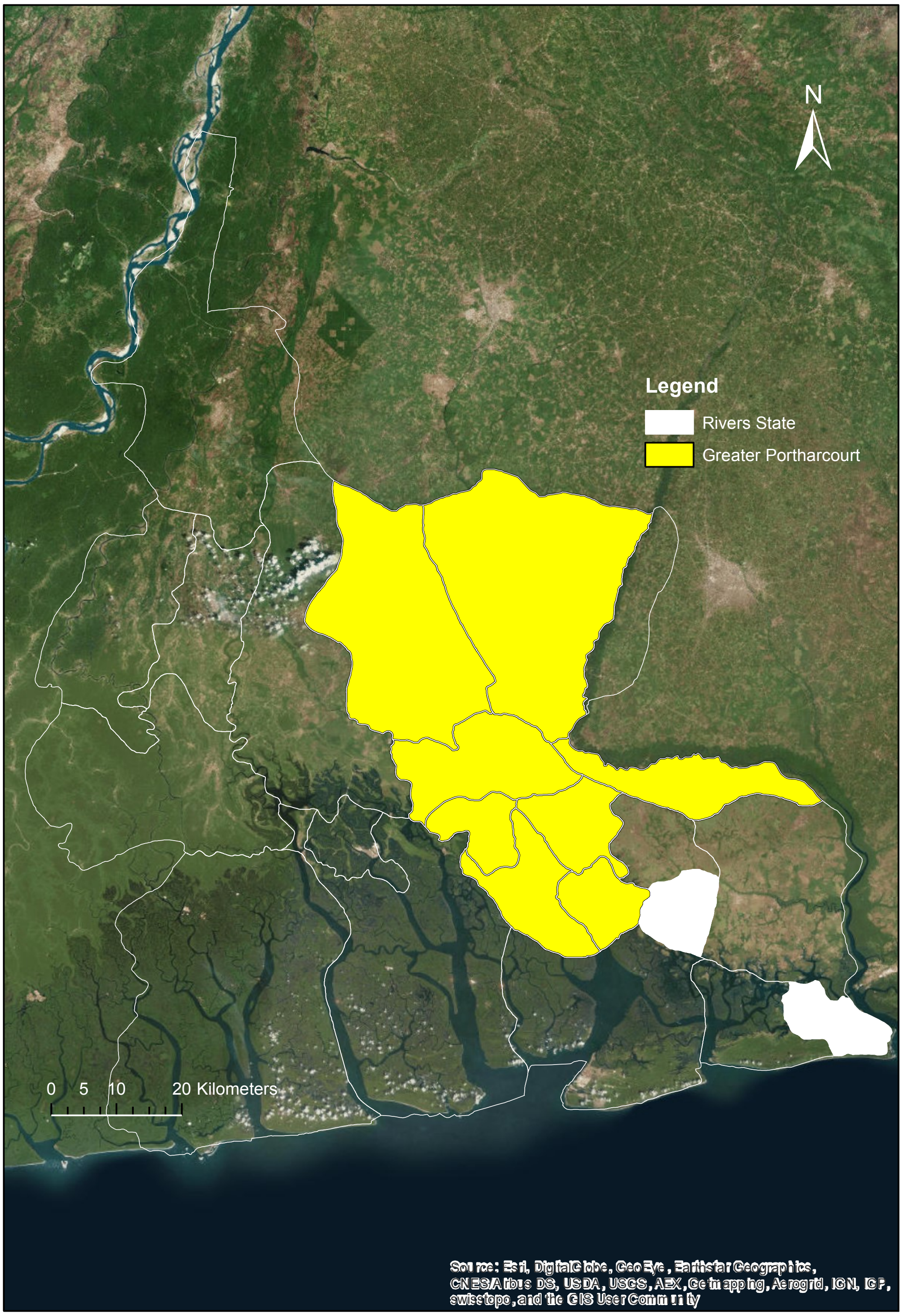


Figure 3.4 Year 2013 base map and year 2001 administrative boundaries map of local government areas that make- up Greater Port-Harcourt. Source: ESR1 (2015)/ Rivers State Ministry of Land and Housing (1995).

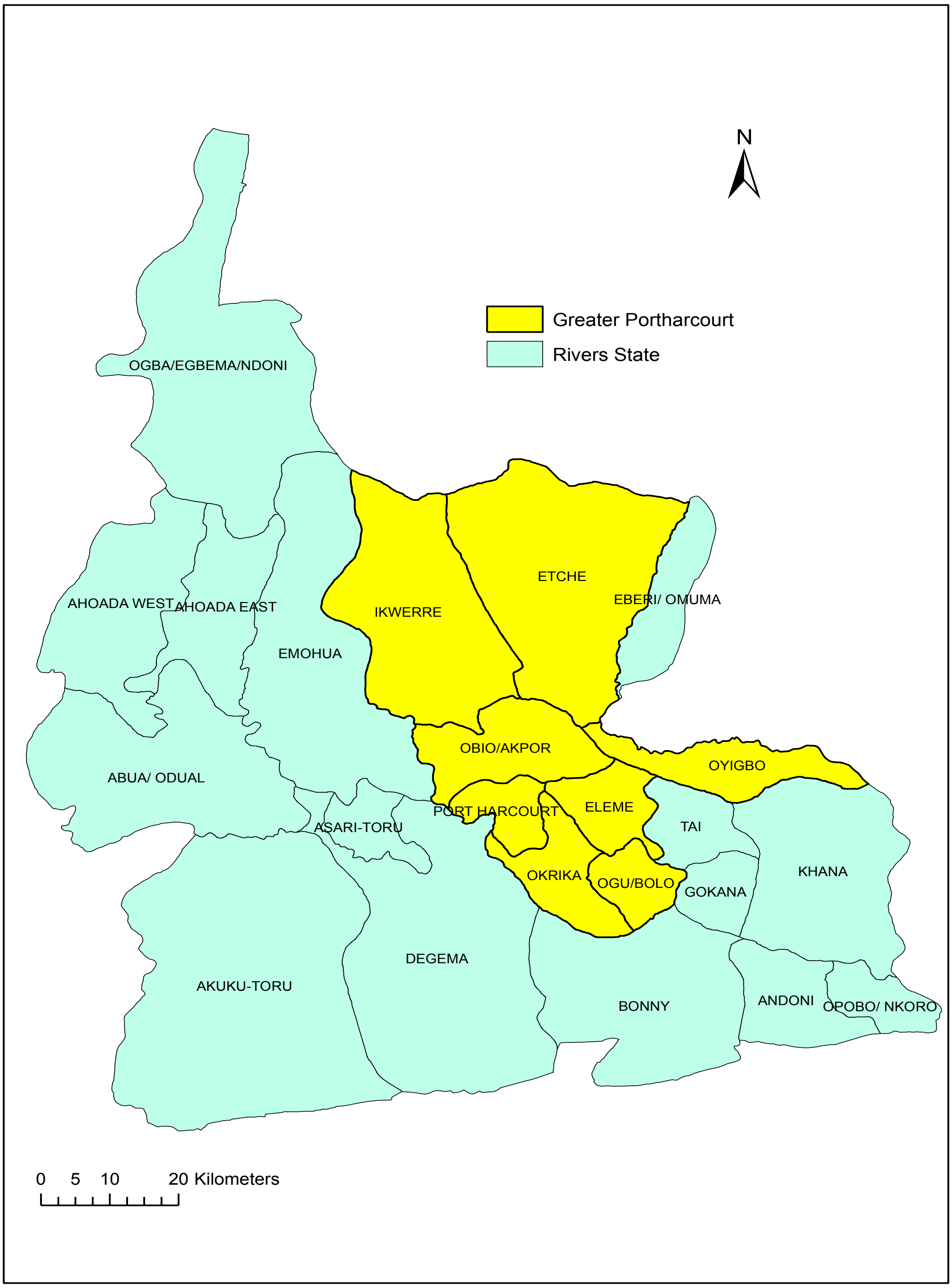


Figure 3.5 Polygon map of River State and the eight Local Government Areas in the Greater Port-Harcourt. Source: Rivers State Ministry of Land and Housing (1995).

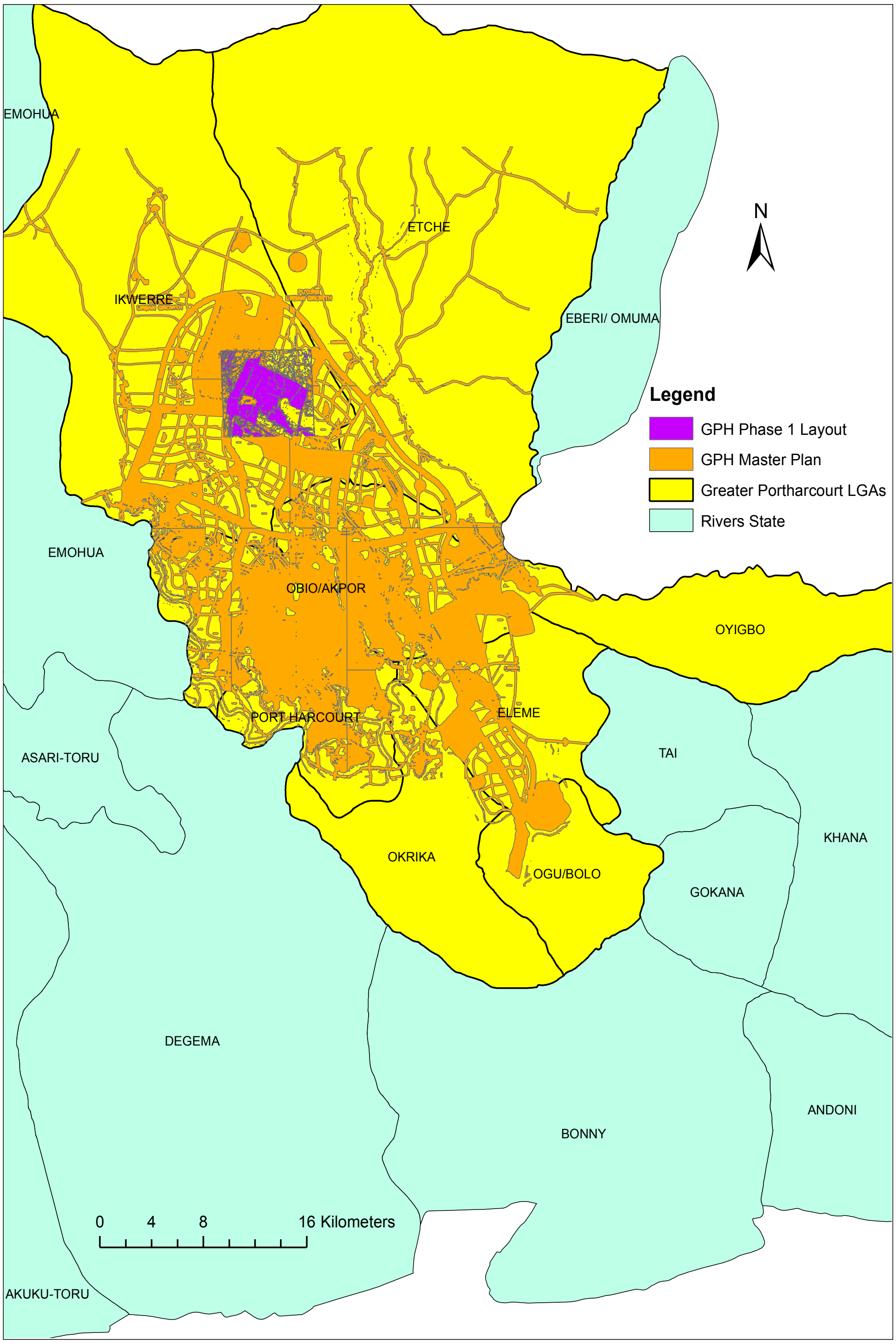


Figure 3.6 Map showing the location of Greater Port-Harcourt City and Phase-1 project area in River State. Base polygon map is the 1995 administrative boundary map. Source GPHDA (2010)/ Rivers State Ministry of Land and Housing (1995).

3.3 THE DEMOGRAPHIC SETTING.

3.3.1 Influx, population growth, housing and life expectancy.

Influx.

Port-Harcourt city in 2016 house about two million people and is one of two largest cities that experience the highest influx of people in the Niger Delta (NDDC, 2006, Demographia, 2016). Industrial and commercial activities are reportedly the main precursors of influx of people into the area (Izeogu, 1989; ERML, 2009). It is also one of the fastest growing cities in Nigeria, with more than 70% of all foreign investments in the south-south region derived from activities in the state (ERML, 2009). River State alone contains about 9.26% of the entire population of the Niger Delta, with the highest growth rate of 3.0% per annum (NDDC, 2006). Port-Harcourt is known as one of the most important industrial centres in Nigeria, the ninth highest oil producer in the world. (Izeogu, 1989; NDDC, 2006; Owei et al., 2010). As the ninth highest oil producer in the world, it hosts the activities of several multi-national companies such as Shell, Total, Exxon Mobil, Agip, and Chevron (NDDC, 2006). However, a gamut of studies have commented on the impact of influx, including: congestion, overcrowding, urban sprawl, environmental degradation and conflict (Izeogu, 1989; NDDC, 2006; UNDP, 2006; ERML, 2009; Theis et al., 2009; Obinna et al., 2010; Owei et al., 2010; Ede et al., 2011; UNEP, 2011; Eludoyin and Weli, 2012; Mmom and Fred-Nwagwu, 2013; Elenwo and Efe, 2014; Enaruvbe and Ige-Olumide, 2014; Wizor, 2014; Akukwe and Ogbodo, 2015; Ikechukwu, 2015).

Population.

The city has witnessed an exponential growth with an annual population growth rate of 3.0% by (NDDC, 2006), the population of Port-Harcourt city has surged from an estimated 180,000 people in 1963 to about 2 million in 2016 (Demographia, 2017), and by 2020, the population of 3 million is expected to rise to about 7 million in the entire Rivers State (NDDC, 2006). It falls within the one to five million size class in the United Nation's World Urban Prospect (Figure 3.7) The population of the entire River State was about three million in 2006 and it is projected to rise to over seven million people by 2020 (see Table 3.1). The 2006 growth rate of 3.0% per annum in the area is higher when contrasted with the African average of 0.98 between 1990 and 2014 (UNDESA, 2015), see Appendix 3.1. A local social survey in 1989 revealed that migrants accounted for 72% of the city's population, where 65% of this migrant

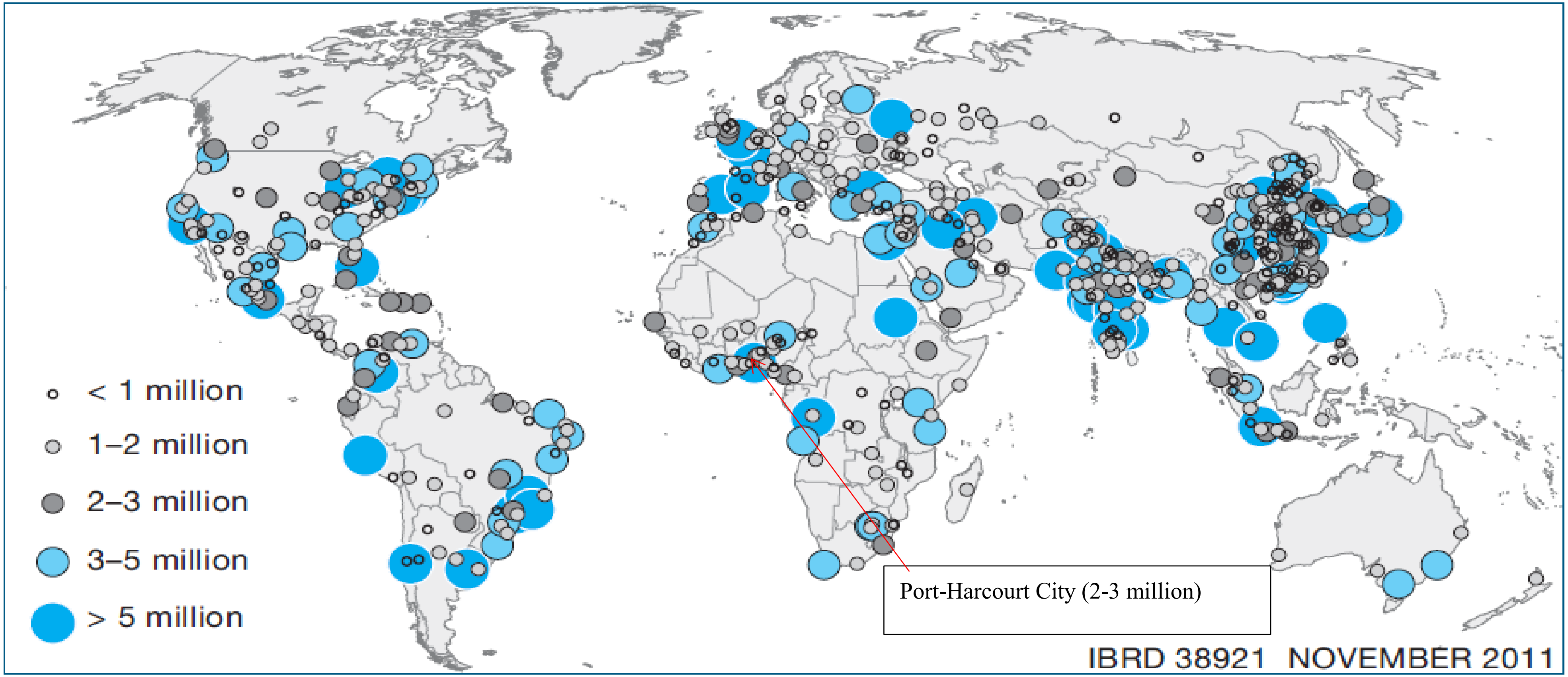


Figure 3.7 Map showing the location of Port-Harcourt urban agglomerations with more than 750,000 inhabitants. It shows the population of Port-Harcourt is between 2-3million. Source: United Nation Department of Economic and Social Affairs (2012).

population emanated from rural areas (Izeogu, 1989). According to the UN, the rural population in this area will continue to decline until 2050 UNDESA (2015), due to rural-urban migration. This implies that the rural population contribute considerably to the rapid influx of people in Port-Harcourt. Moreover, Figure 3.7 indicates Port-Harcourt falls into areas of high agglomeration, greater than 750,000 inhabitants. As stated in the caption, the data shows that population of Port-Harcourt ranges between 2-3million and is not one of the largest. Jha et al. (2012) argue that an area with high agglomeration is subject to increased flood risk due to the potential for increasing population to be exposed to flooding within the city.

Table 3.1 Population projection for states within the Niger Delta Region based census data. The projection for River State is the highest among Niger Delta states. The population projection for River State is under 5 million in 2005 and over 5 million in 2011. Source: N/B: the 2012 data is the latest population data available for the country. The NDDC, 2006/ National Bureau of Statistics, 2012.

State	City Capital	Land Area Km^2	Projected Population to 2005	Projected Population to 2011
Abia	Umuahia	4,877	3,230,000	3,256,642
Akwa-Ibom	Uyo	6,806	3,343,000	4,625,119
Bayelsa	Yenegoa	11,007	1,710,000	1,970,487
Cross River	Calabar	21,930	1,710,000	3,344,410
Delta	Asaba	17, 161	3,594,000	4,675,526
Edo	Benin	19,698	3,018,000	3,700,704
Imo	Owerri	5,165	3,342,000	4,609,038
Ondo	Akure	15,086	3,025,000	4,020,965
Rivers	Port-Harcourt	10,378	4,858,000	5,198,716
Total		112,108	28,856,000	35,401,607

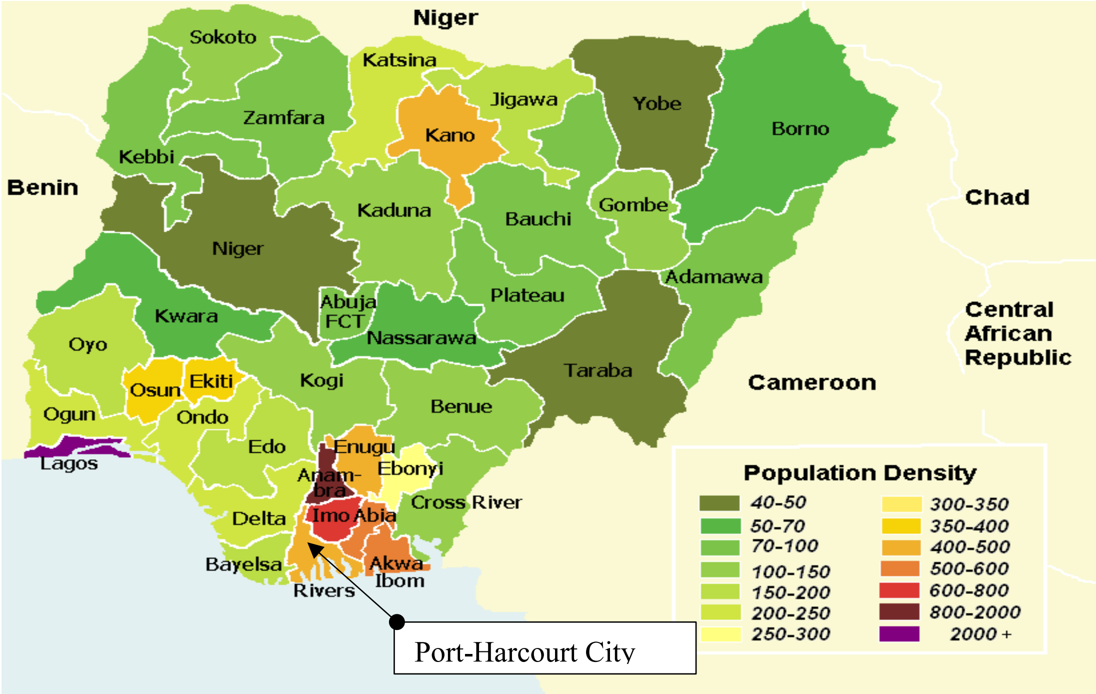


Figure 3.8 Map showing the population density of cities in Nigeria in 2008. Population density of Port-Harcourt is between 400-500 people per sq. km of land area (Source: Marcel Krüger, 2008).

Besides the rapid population growth, Port-Harcourt the largest city in the south-south region of Nigeria is also experiencing rapid physical expansion (Figure 3.9). The city of Port-Harcourt grew steadily from 15.54 km^2 in 1914 through to 39.60 km^2 in 1975 and 106.77 km^2 in 2012 to a metropolis spanning more than 360 km^2 (Izeogu, 1989; Mmom and Fred-Nwagwu, 2013). Appendix 3.2 and 3.2 show urban land conversion in the area between 1986 and 2007. Like other metropolitan cities of the world, urbanisation from planned and unplanned development due to rising population growth often strain the urban landscape (Abam, 2001; NDDC, 2003; Ologunorisa 2004; Chen et al., 2009; Bariweni et al., 2012). In addition, Jha et al. (2012) argued that as cities and towns swell and grow outwards, accommodations and population increase. Moreover, large-scale urban expansion are often accompanied by unplanned developments in floodplains, coastal and inland areas. Likewise, the enlargement of Port-Harcourt City is expected to develop in a similar pattern.

Furthermore, large portions of the city remain undeveloped owing to a number of factors such as natural and physical constraints e.g. excessively ponded areas and marshlands (Theis et al., 2009; Ede et al., 2011). As a result, planned developments have been limited to a part of the city. Much of the unplanned growth has occurred in the urban fringes in less desirable areas termed slums or squatter settlements. Squatter settlements make up 65% of the city's settlements (Obinna et al., 2010). The growth of slums was triggered by socioeconomic and physical factors such as the high cost of living, the high cost of available land as well as the continued desire for traditional, water-based livelihoods of people from riverine communities (Obinna et al., 2010; Wizor, 2014). Migrants from riverine communities have resorted to squatting in informal shelters on waterfronts in the south of the city (Figure 3.10), creating high densities whereas migrants from upland areas tend to build informal settlements in the north of the city, bringing about continuous, low-density developments (Obinna et al., 2010).

Generally, there are different types settlements in the city (ERML, 2009), ranging from high modern to low-income squatter settlements. Majority of the housing falls into the middle to low-income grouping. There are over 30 neighbourhoods in the city. Thirteen of the squatter settlements comprise 30,000 dwelling units that harbours as many as 275,000 people (ERML, 2009). Squatter settlements are characterised by the deplorable housing, lack of space, infrastructure and basic services. The means to deal with slums remain a dilemma for the Government. Accordingly, slums are located in city centres, peripheral, suburban or peri-urban areas. These areas lack suitable housing, infrastructure and service provision that could increase the risk of flooding. Flooding in the city is a common occurrence; a minor rainfall event causes major flooding problems around the city (Eludoyin and Weli, 2012; Mmom and Fred-Nwagwu, 2013; Akukwe and Ogbodo, 2015). The limited space, poor town planning and implementation of flood/erosion policy have led to the developments of many structures within flood prone areas (Akukwe Thecla; Theis et al., 2009; Obinna et al., 2010; Ede et al., 2011; Akukwe and Ogbodo, 2015).

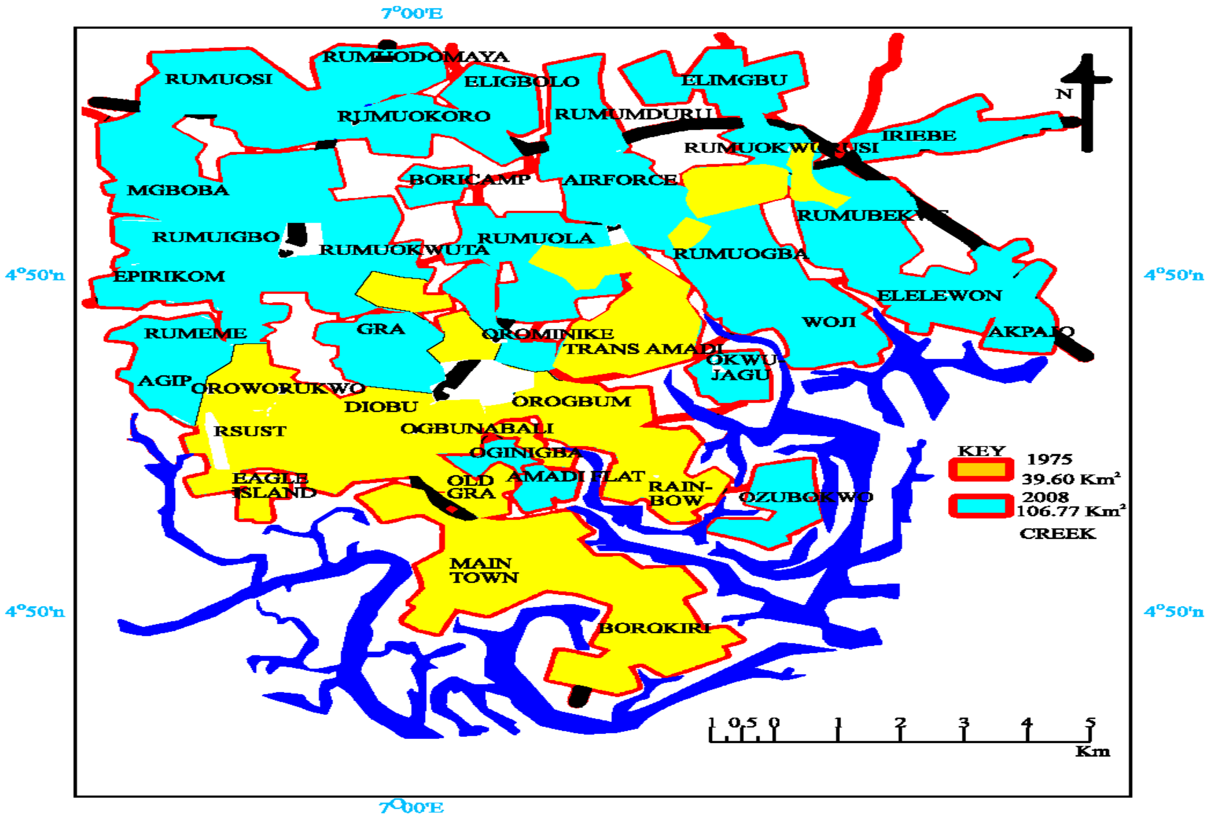


Figure 3.9 A sketched map of old Port-Harcourt City showing spatial growth between 1975 and 2008 The city grew from to 39.60 km² to 106.77 km² (Baadom, 2015).

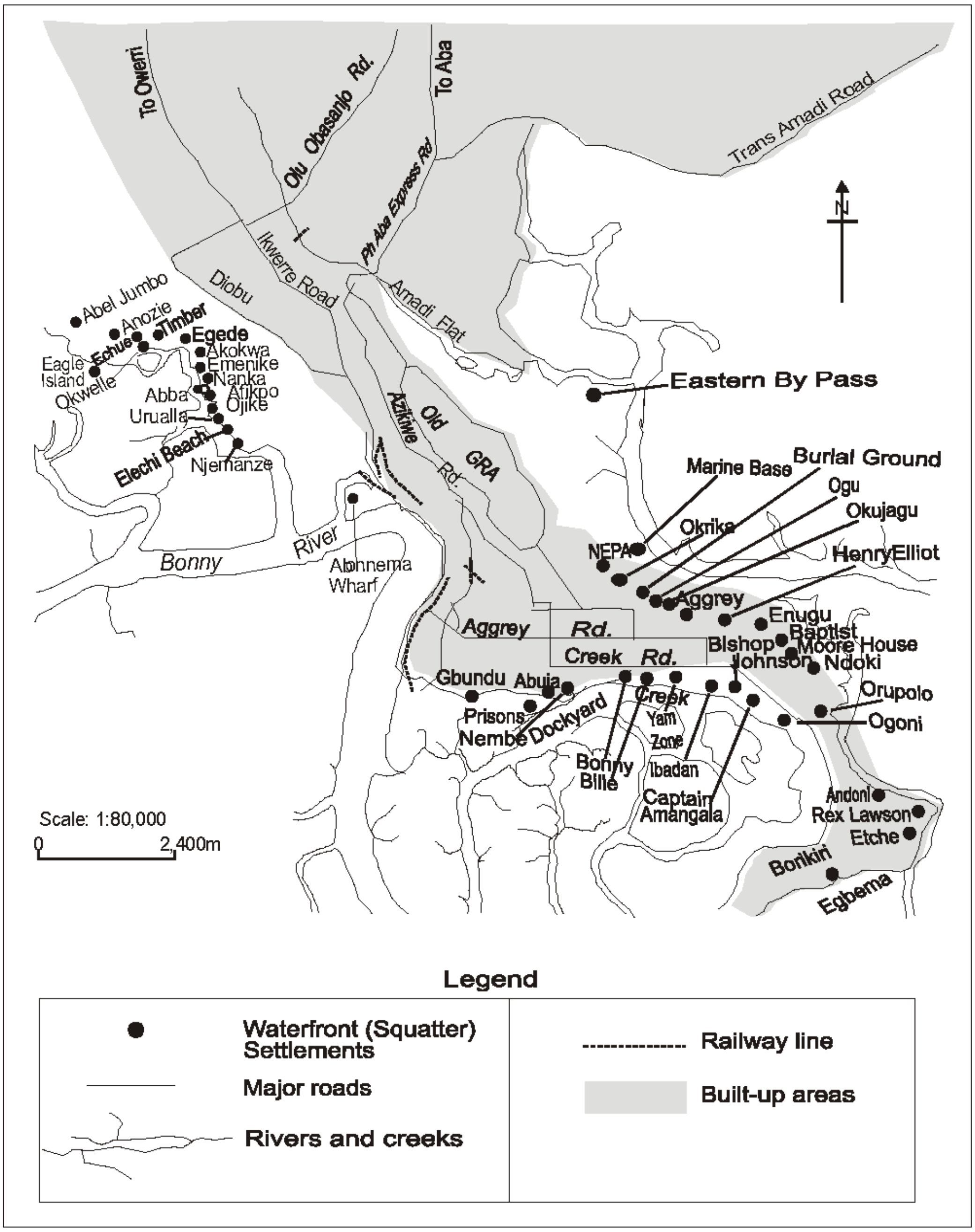


Figure 3.10 A 1:80,000 map of South-east Port-Harcourt showing the distribution squatter settlements along waterfronts. Prominent areas include the Borokiri area, Bonny waterside and Gbundu areas (Imbasi, 1994).

Life Expectancy.

Life expectancy is low and is attributable to socioeconomic problems, mainly due to poverty (UNDP, 2006). There has been a decline in life expectancy from 60 years down to 43 years (UNDP, 2006). Generally, with the projected population and high rates of poverty, life expectancy may continue to decline.

3.4 BIOPHYSICAL CHARACTERISTICS.

3.4.1 Meteorological and Climatic.

The climate of Port-Harcourt falls under Af, that is an equatorial monsoon climate, according to the Köppen-Geiger climate classification (Kottek et al., 2006). Rainfall is significant for most months of the rainy season (April to Nov), but short spells of dry season interject (Nov-Mar) with little effect. Usually, the mean monthly rainfall is highly varied in the area, with an average of 2400mm (Ayotamuno et al., 2006). Rainfall is the major cause of flooding in the area (Akukwe Thecla; SPDC, 2007; Chiadikobi et al., 2011). Occasionally, severe harmattan bring droughts of up to one month in the area. January is the driest month and averages to about 36 mm of rainfall, while the wettest month is September and averages to about 414 mm (SPDC, 2007; ERML, 2009). On average, the annual mean air temperature is 27°C (22.2 – 33.4°C) (SPDC, 2007). Air temperature is usually moderate at the peak of the wet season (July-September) due to more cloud cover, but extreme during the dry season (November-March). Relative humidity is very high, ranging from 96% (maximum) at 2000 – 1400 GMT to a 71% (minimum) at noon (1400 GMT). The wettest months (June – October) experience the highest relative humidity. Conversely, dryer months (November – March) experience the lowest. Wind speed mostly moves south-westerly and southerly at 1.5 m/s. Diurnal wind runs in the area and peaks at noon. Higher in the day and lower at night time (SPDC, 2007; ERML, 2009).

3.4.2 Land use/Land cover and Land take.

Land use/land cover change (LULC), urban expansion and land take are major concerns of the development in the GPH area (ERML, 2009; Obinna et al., 2010; Wizor, 2014). Previous remote sensing studies have proven that the area has historically experienced significant negative changes in land use/land cover (Izeogu, 1989; Owei et al., 2010; Eludoyin et al., 2011; Mmom and Fred-Nwagwu, 2013); see Appendices 2.2 and 2.3. For instance, previous LULC analysis by Mmom and Fred-Nwagwu (2013) showed that built up areas in Port-Harcourt increased from 13% in 1986 to 22% in 1996 and 24% in 2007. In Obio/Apko alone, a recent study demonstrated that the built-up area, secondary forest and water and land use types increased by 74.55%, 5.88%, and 3.43%, respectively, while agricultural land, primary mangrove, and sparse vegetation, land use types declined by 45.34%, 37.06%, 43.06%

and 8.09% respectively between 1986 and 2000 (Eludoyin et al., 2011). These rapid changes are driven mainly by socioeconomic factors such as land tenure system, livelihood, population growth and rapid industrialisation (Mmom and Fred-Nwagwu, 2013). Considering the limited land and projection of urban population in the area, land take and LULC changes as a result of the development are likely to have significant negative environmental impacts.

3.4.3 Hydrology/Water flooding.

In addition to impacts on demography, housing and land take, urbanisation impact on the hydrology of the wetland is considered a major issue in the Greater Port-Harcourt area (Abam, 1999; Abam, 2001; Chiadikobi et al., 2011; Ede et al., 2011; Akukwe and Ogbodo, 2015). As stated in Chapter 2, urban expansion through clearing and replacement of vegetal cover during the construction and operation phases of the development cycle are likely to alter the hydrological processes by increasing surface water runoff at varying spatial and temporal scales (Chen et al., 2009; Akukwe and Ogbodo, 2015). Vegetal land cover replacement with tarmac in built-up areas usually play a role of decreasing the infiltration capacity, thereby altering the runoff, which finally results in increased flooding of river channels (Akukwe Thecla). See Chapter 5 for in-depth analysis.

The Niger Delta is a coastal environment and flooding is the most frequent and life-threatening environmental hazard in the region, aggravated by land use changes (Abam, 2001a; Chiadikobi et al., 2011; GFDRR, 2013; Elenwo and Efe, 2014; Akukwe and Ogbodo, 2015). A recent example was the July 2012 flood caused by heavy rainfall, leaving 363 people dead, 5,851 injured and nearly four million people displaced in Nigeria including Port-Harcourt (GFDRR, 2013). Historically, frequent episodes of flooding result from a combination of factors such as tidal surge, dam floods (rarely) and storm flood from heavy rainfall (frequent), (FAO, 1997; Ologunorisa 2004; Uyigue and Agho, 2007; Obowu and Abam, 2014). Hence, recent studies have suggested that the frequency and severity of such floods are expected to increase due to climate change (Uyigue and Agho, 2007; GFDRR, 2013).

For instance, the IPCC projections imply that climate change caused by the emission of greenhouse gases (GHG) is expected to affect drought in the northern part of Nigeria and flooding in the south where the Niger Delta is location (Uyigue and Agho, 2007; Akinro et al., 2008; Nzeadibe et al., 2011). The above studies also suggest that economically deprived regions, such as the Niger Delta are the most vulnerable due to the regions low adaptive capacity. The Niger Delta is also very susceptible to the effects of climate change as a result of its coastal location. The region is already faced with flooding as a result of a rise in sea levels (Uyigue and Agho, 2007; Akinro et al., 2008; Nzeadibe et al., 2011).

Therefore, drastic land use changes from the ongoing and future GPH developments are most likely to aggravate flooding in the area.

3.4.4 The Niger River drainage system.

Rivers in the GPH basin are at the lowest reaches of the Niger River system (Figure 3.11), draining much of West Africa (Abam, 2001; Nkeki et al., 2013). The entire river system extend to ten West African countries, with the largest drainage area (27%) enclosed in Nigeria. The river system spans 4100 km^2 in an area cover 7.25% of the African continental landmass (Nkeki et al., 2013). In Nigeria, the drainage system is divided into eight hydrographic regions, including Niger North, Niger Central, Upper Benue, Lower Benue, Niger South, Western Littoral, Eastern Littoral and Lake Chad regions (NIHSA, 2012), of which GPH is situated in the Niger South (Figure 3.12). Niger South is the most downstream region and downstream basins such as this are considered the most vulnerable to flood risk due to upstream developments (Abam, 1999; Ologunorisa 2004; NIHSA, 2012; Nkeki et al., 2013).

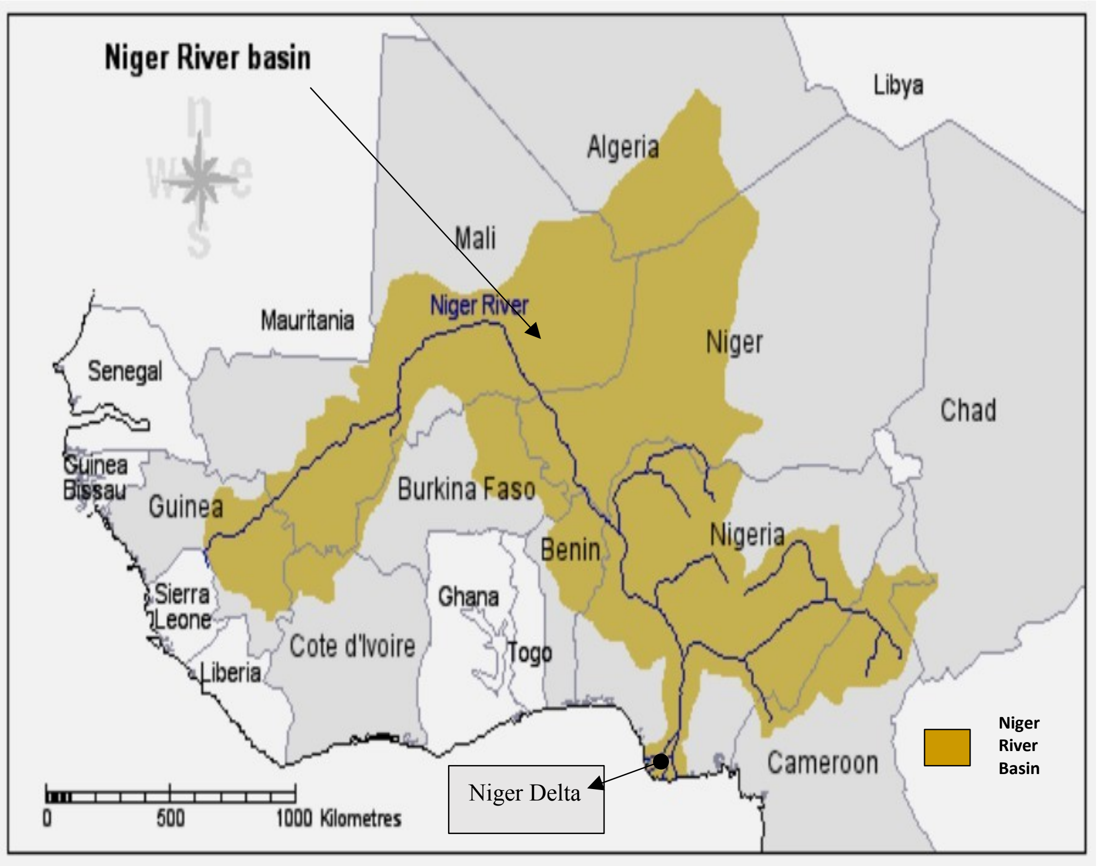


Figure 3.11 A Sketch map of West Africa showing the Niger Delta and a dense network of rivers in the Niger River Basin (Pojer, 2014).

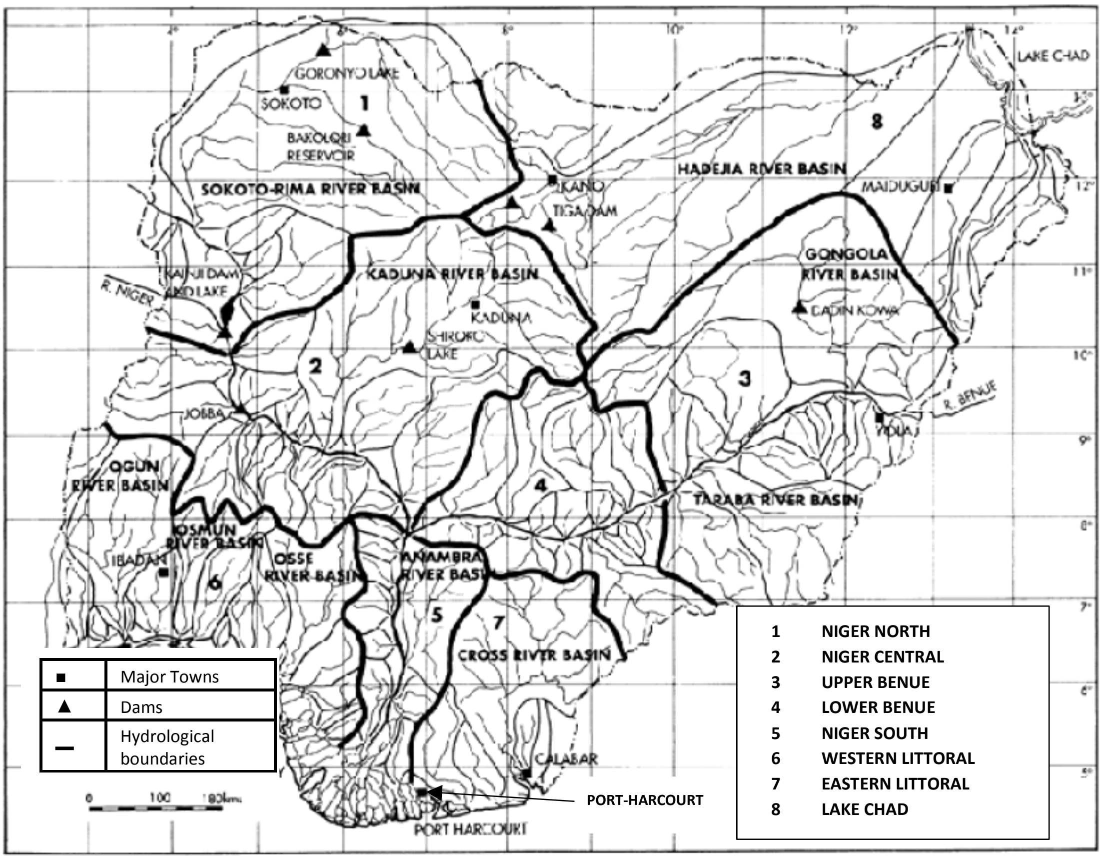


Figure 3.12 Map of River Niger divided into Eight hydrographical regions including the Niger North, Niger Central, Upper Benue, Lower Benue, Niger South, Western Littoral, Eastern Littoral and Lake Chad regions. Port-Harcourt is situated in Niger South (Idu, 2015).

3.5 DESCRIPTION OF THE GPH WATERSHED

A dense network of rivers and creeks dividing the area into different drainage zones (Abam, 1999; NDDC, 2006) dissects greater Port-Harcourt. The watershed is a lowland comprised of five (5) major basins and 39 sub-basins spanning 4,821km^2 delineated for study (Figure 3.13-3.15). The spatial extent used for hydrologic and hydraulic analysis covers 44% of the total land area of the state. The largest basin is about 344km^2 and the smallest about 14km^2 large. The total number of river reaches as delineated are 37. The River Niger partly discharges its water and sediments through the GPH area into the Atlantic Ocean (Reijers *et al.*, 1997; Abam, 1999). Regarding drainage zones, Greater Port-Harcourt is characterised by the dry mainland, poorly drained seasonal swamps, and flooded areas (Abam, 1999). Most of the main rivers are in a North-southerly direction. The area is characterised by a flat topography underlain by superficial soil consisting of silty clays and silty sand soils (Abam, 1999). On average, the water table is less than 10m than below ground level.

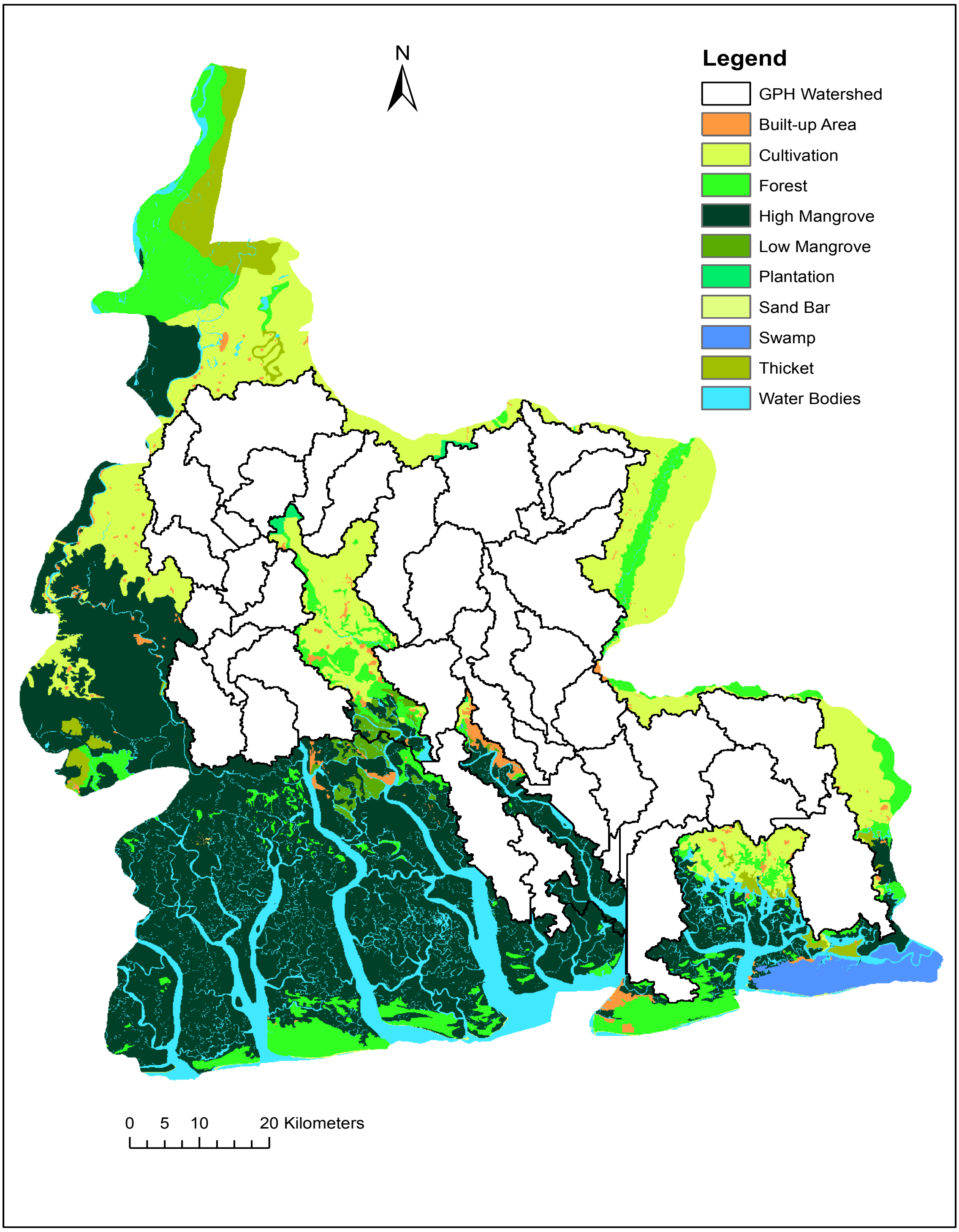


Figure 3.13 Map of the study area showing land use/land cover classes derived from the 1995 polygon map. Source: Rivers State Ministry of Land and Housing (1995).

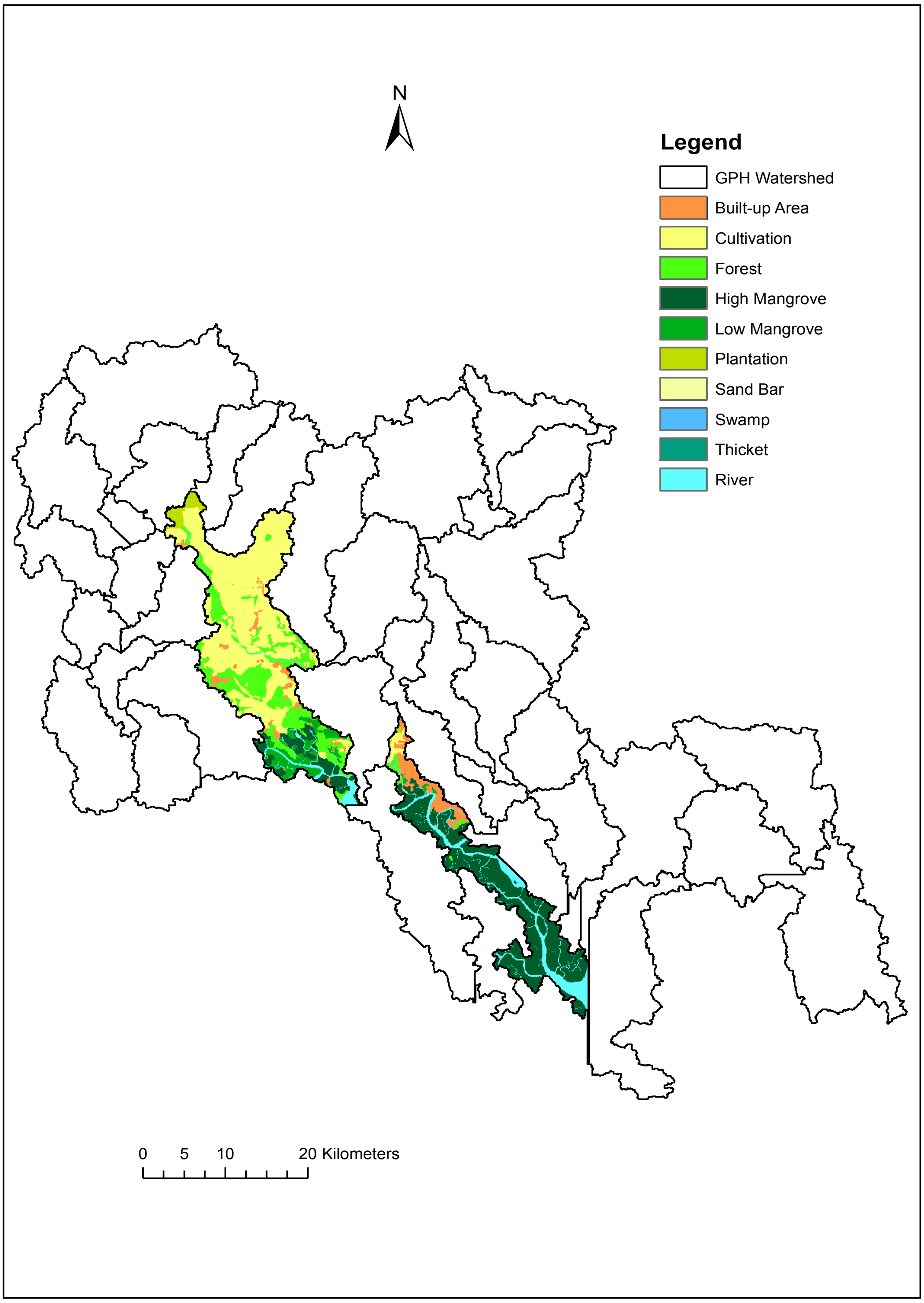


Figure 3.14 Map of the Greater Port-Harcourt watershed showing LULC classes clipped to the watershed area. Source: Rivers State Ministry of Land and Housing (1995).

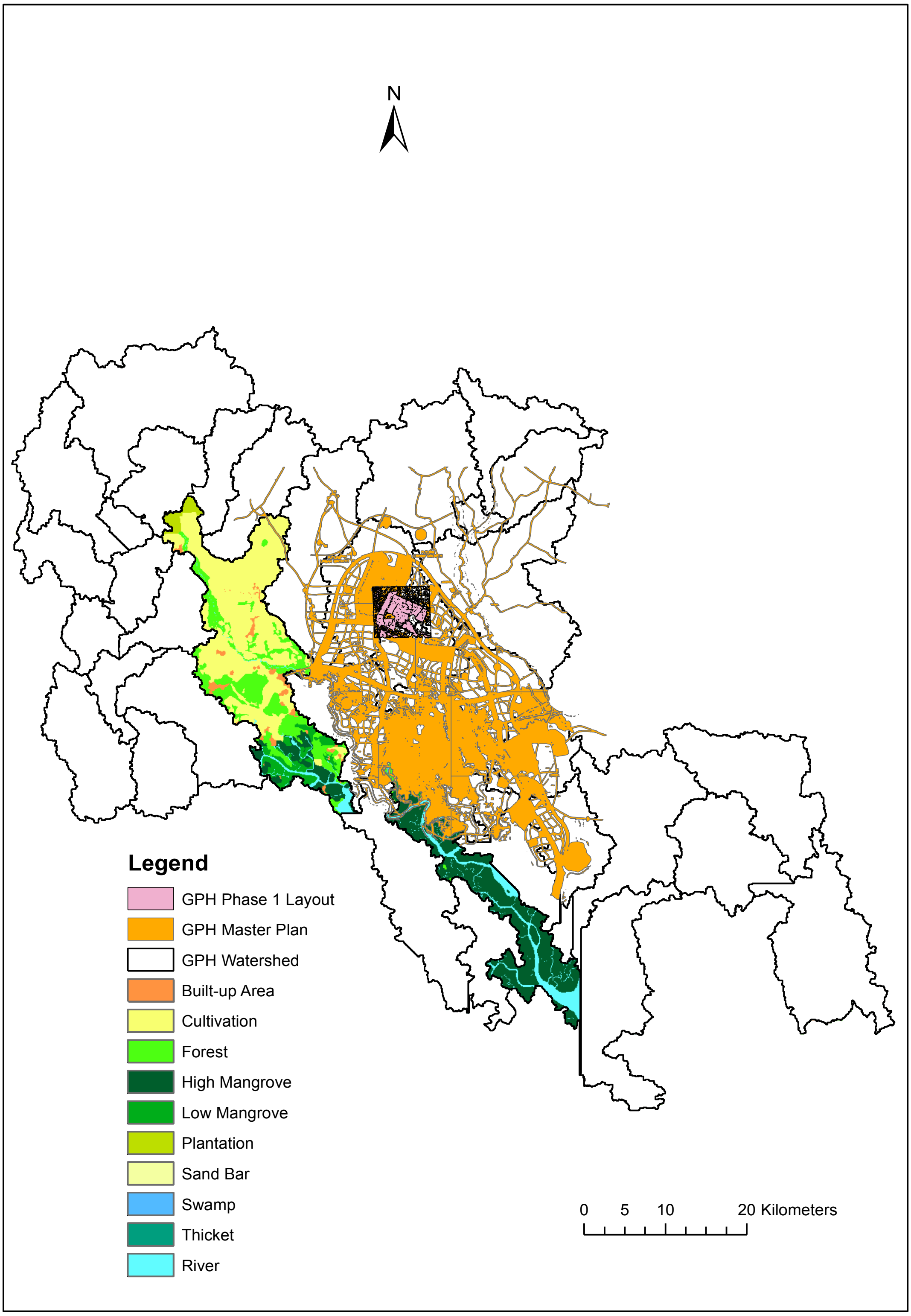


Figure 3.15 Map of the Greater Port-Harcourt watershed showing the location of Phase-1 and the Masterplan. Source: Rivers State Ministry of Land and Housing (1995).

As a lowland, the sub-basins are very vulnerable to external perturbations which could induce flood risk. Abam (1999); Uyigue and Agho (2007); NIHSA (2012) and Akukwe and Ogbodo (2015) have suggested that flooding in the area is predominantly the result of excessive precipitation, topography, urban developments, poorly maintained and inadequate drainage in addition to soil permeability.

3.5.1 Ecology and Biodiversity.

The Niger Delta is well known as an ecologically fragile zone comprising of a vast array of diverse ecological types divided into four ecological zones (Abam, 1999; NDDC, 2003; Adekola and Mitchell, 2011; Obowu and Abam, 2014). The ecological zones of the entire delta are primarily: mangrove forest, freshwater swamp, lowland rainforest, and savannah and montane while the ecological zones are GPH, predominantly mangrove (coastal vegetation), freshwater swamp forest and lowland rain forest (NDDC, 2003; Bariweni et al., 2012). According to Abam (1999), these ecological types are defined by hydrology, soil type and elevation. The vegetation of the Phase-1 area is mainly lowland rainforest and freshwater swamp forest. The lowland rainforest consists of cassava farms and fallow lands comprising of oil and raffia palms and stand-alone trees. The freshwater swamp forests contain low to medium trees, less than 30 m in height. Figure 3.16 shows location of Port-Harcourt in Nigeria's Ecological Zones, while Figure 3.17 shows mangrove ecosystem in the south of Greater Port-Harcourt City.

Studies have shown that unregulated developments can have adverse impacts on the ecology of an area (Calder, 2007; Lin et al., 2009). For instance, land-use alterations resulting from developments can modify the existing ecological boundaries. Again, the impact on ecology due to vegetation clearing (during the construction phase of a development) can result in loss of biodiversity, loss of habitat and fragmentation, besides the impact on ecosystem services (Theobald and Hobbs, 2002; Calder, 2007; Adekola and Mitchell, 2011; Kuenzer et al., 2014). Besides, mangrove forest in the delta forms an important ecosystem occupying the intertidal zone near the coast (Abam, 1999; NDDC, 2003). Like in the GPH area, mangroves provide unique functions such as shoreline stabilisation, and support for wildlife populations, however, vegetation clearing may likely affect these functions (Carter, 1986; Abam, 1999; Varnell et al., 2003; McLaughlin et al., 2014). Moreover, Abam (1999) argues that urban flooding may significantly contribute to the seaward movement of fresh water downstream which may result in salt water dilution and recession. Saltwater dilution may affect the mangrove ecosystem. Therefore, urbanisation could affect the ecosystem beyond the direct impact on hydrology.

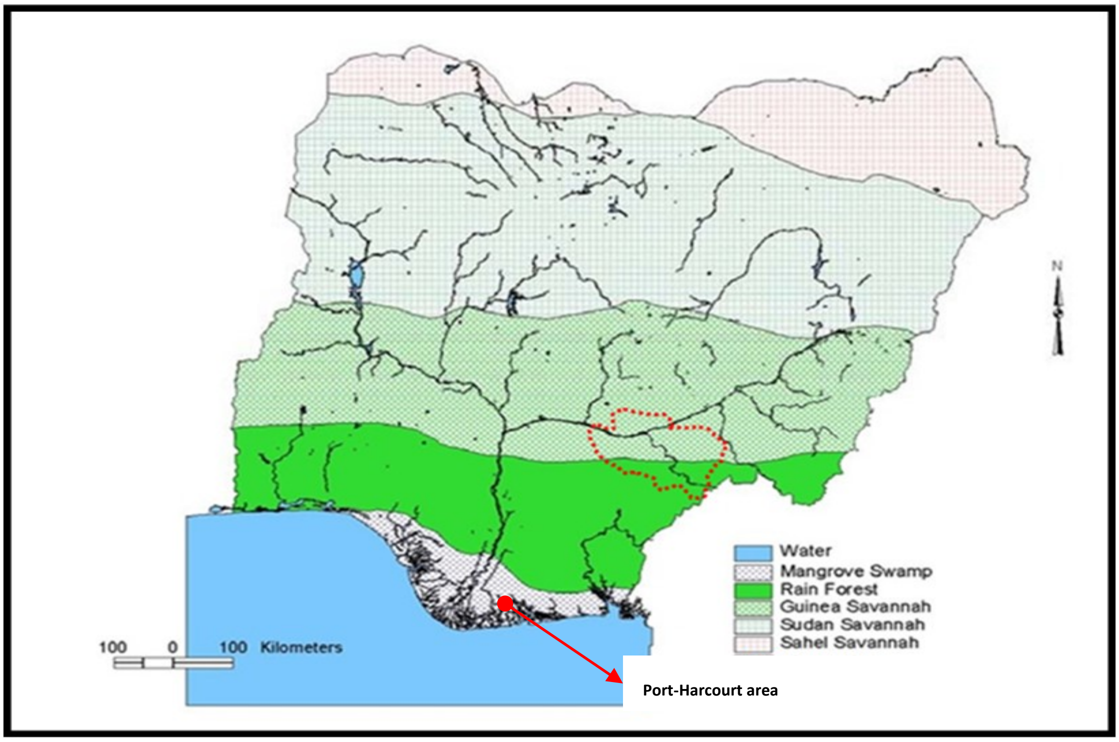


Figure 3.16 Diagram showing the location of Port-Harcourt in Nigeria's Ecological Zones, Source: Ujoh (2014).

Figure 3.17 Mangrove Ecosystem as seen in the South of Greater Port-Harcourt City (Photo taken in 2013).

3.5.2 Geology.

The geology of the Niger Delta has been extensively studied (Short and Stauble, 1967; Weber and Daukoru, 1975; Amadi et al., 1989; Doust, 1990; Reijers et al., 1997; Abam, 1999). Geologically, the rivers and sedimentary basins of the GPH area are located at the continental margin of the Gulf of Guinea, making it one of the world's most prolific tertiary deltas in terms of water and hydrocarbon yields (Reijers et al., 1997). The delta sequence comprises an upward-coarsening regressive association of Tertiary clastic sediments up to 12 km thick (Short and Stauble, 1967; Reijers et al., 1997). It is often divided into three lithofacies. First, the intercalation of marine claystones and shales of unknown thickness at the base called the Akata formation (Figure 3.18). Second, the intercalation of sandstones, siltstones and claystones in the middle called the Agbada formation. Third, an outcrop of alluvial sands at the top called the Benin formation. (Amajor, 1991; Reijers et al., 1997). The Benin formation largely consists of continental sand, alternating with pebbly layers and a few clay beds. This unit consists of unconfined aquifers of high ground water yield (Amajor, 1991).

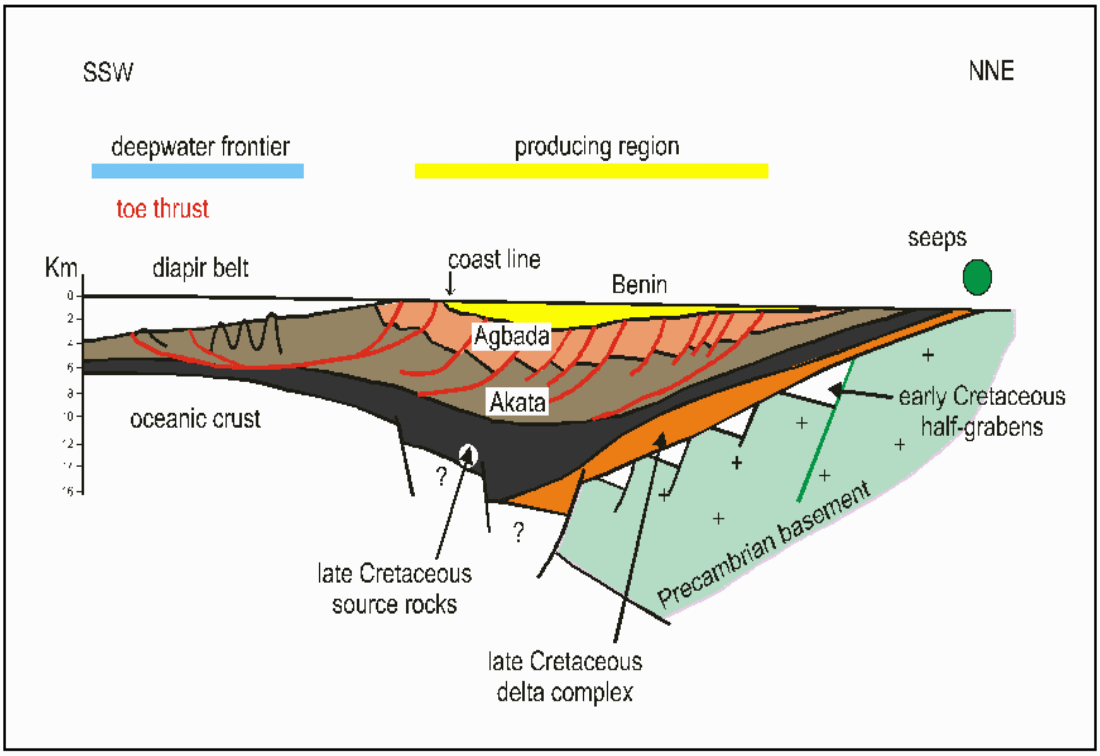


Figure 3.18 The geology of the Niger Delta showing the three main lithographic facies namely, the Akata, Agbada and Benin formation (Cameron, 1999).

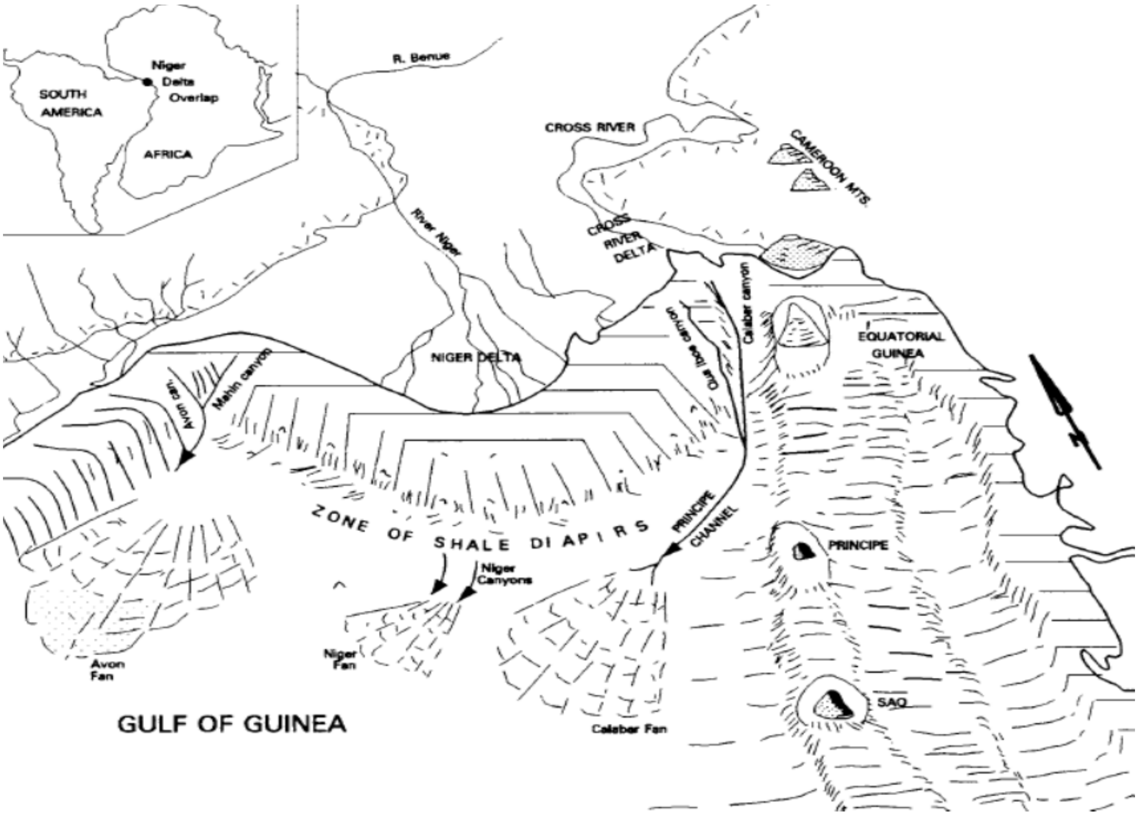


Figure 3.19 Sketch of the geology of the Niger Delta showing main channels and sedimentary basins (Reijers *et al.*, 1997).

From the Eocene to present, there has been a strong relationship between hydrographic and sedimentary processes (Reijers et al., 1997). For example, within that geologic period, tertiary sedimentary deposits in the area ultimately progressed southwards in the same direction with river flowing towards the Atlantic oceanic crust (Figure 3.19). These sedimentary deposits are entirely clastic, supplied by the same continental drainage system forming a braided river system in the delta. Coupled with excessive rain, low soil permeability and high water table, the development during construction is likely to encourage runoff due to vegetation clearing since topsoil is vulnerable if devoid of vegetation. Moreover, the upper crust if exposed to storm may eventually increase sediment and nutrient transport into nearby rivers as a result of barren topsoil. Therefore, increased vegetation clearing through urbanisation may significantly affect flooding.

3.6 GPH MASTERPLAN AND PROJECT DESCRIPTION.

3.6.1 Background.

The Greater Port-Harcourt City Masterplan is a 50yr integrated plan designed for the development and integration of the New Port-Harcourt City (see Figures 3.20- 3.23). The integrated Masterplan consists of transport, road, water, storm water, wastewater, land use, social infrastructure and energy (gas and electricity) plans developed to be implemented in three phases. All phases of the developments (including existing and future projects referred to as 'GPHC Development Projects') are scheduled to be completed by 2060 (ERML, 2009). The vision of the plan is "to transform the Greater Port-Harcourt Area into a world class city that is internationally recognised for excellence, and for the area to become the preferred destination for investors and tourists," (ERML, 2009: ES-1).

Spatially, the plan covers an area of approximately 1900 km^2 spanning eight Local Government Areas as stated in section 3.2.3. It includes all of the old Port-Harcourt city and parts of Oyigbo, Okrika, Ogu/Bolo, Obio/Akpor, Ikwerre, Etche and Eleme Local Government Areas (LGAs), (ERML, 2009; GPHCDA, 2010). The New City will be an extension of the old Port-Harcourt city and will allow for urban growth through planning and de-densification of the old city, while gradually integrating both cities into one single unit (GPHCDA, 2008, 2010).

The Greater Port-Harcourt City Development Authority (GPHCDA) is the authority responsible for implementing the GPH Masterplan established by the 'The Greater Port-Harcourt City Development Authority Law' No. 2 of 2009 (GPHCDA, 2010). The GPHCDA have been charged with the responsibility of facilitating the implementation of the GPH Masterplan and developing the New City (GPHCDA, 2010). The objectives of the plan are primarily economic. That is, to enhance the standard of living and well-being of people in the city by transforming it into a functional, efficient, world class city with first-rate infrastructure and delivery of quality services (ERML, 2009; GPHCDA, 2010). The successful implementation of the Masterplan is projected to yield improved commerce options as well as increased investment opportunities. While yielding economic benefits, previous studies have argued that economic developments should also be placed in environmental contexts for the purpose of protecting environmental quality (Glasson et al., 2005; Ede et al., 2011; UNECA, 2011; Akukwe and Ogbodo, 2015).

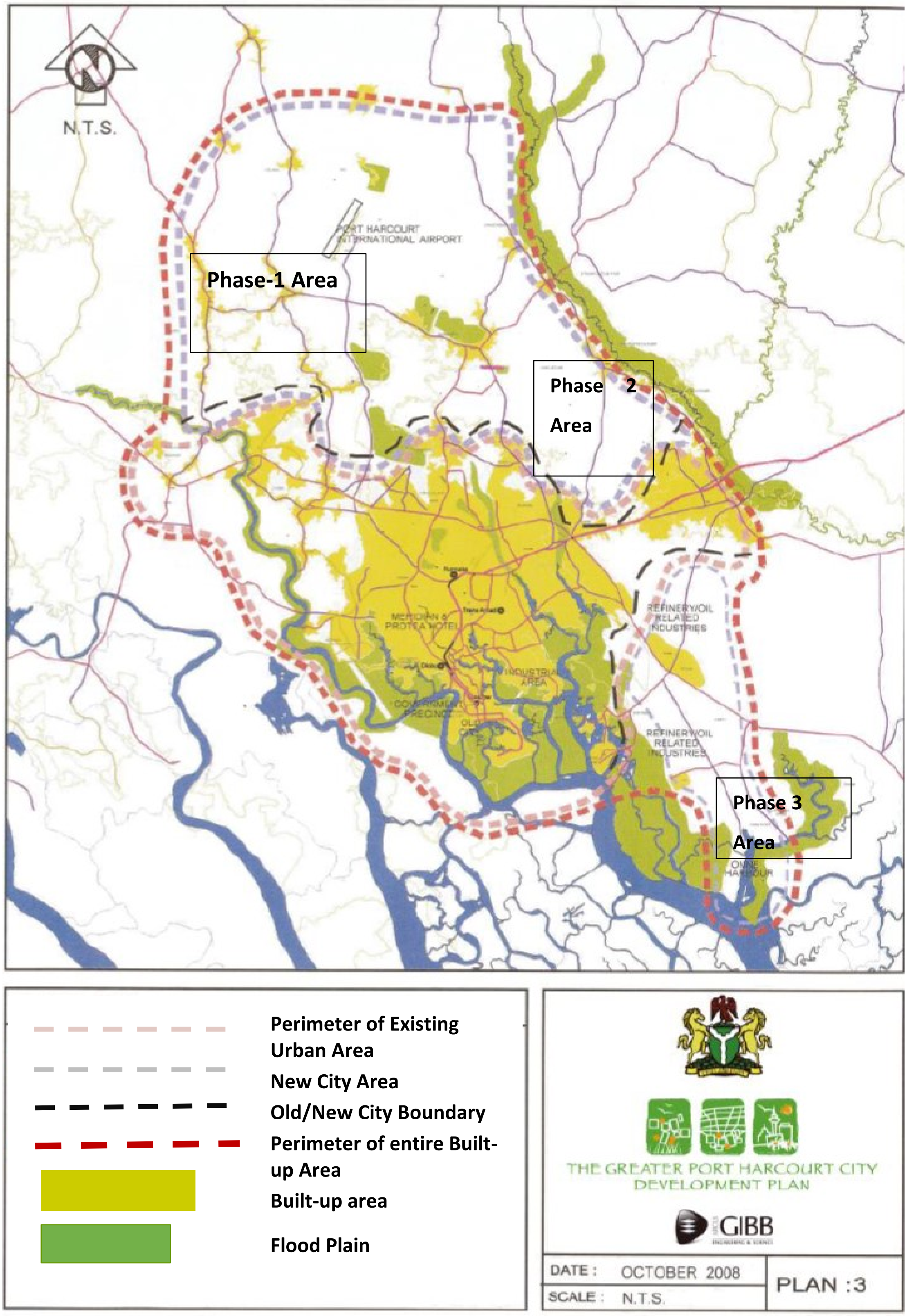


Figure 3.20 Overview map showing the area and perimeter of the old and new city in the Greater Port-Harcourt Masterplan, Source: GPHCDA (2008).

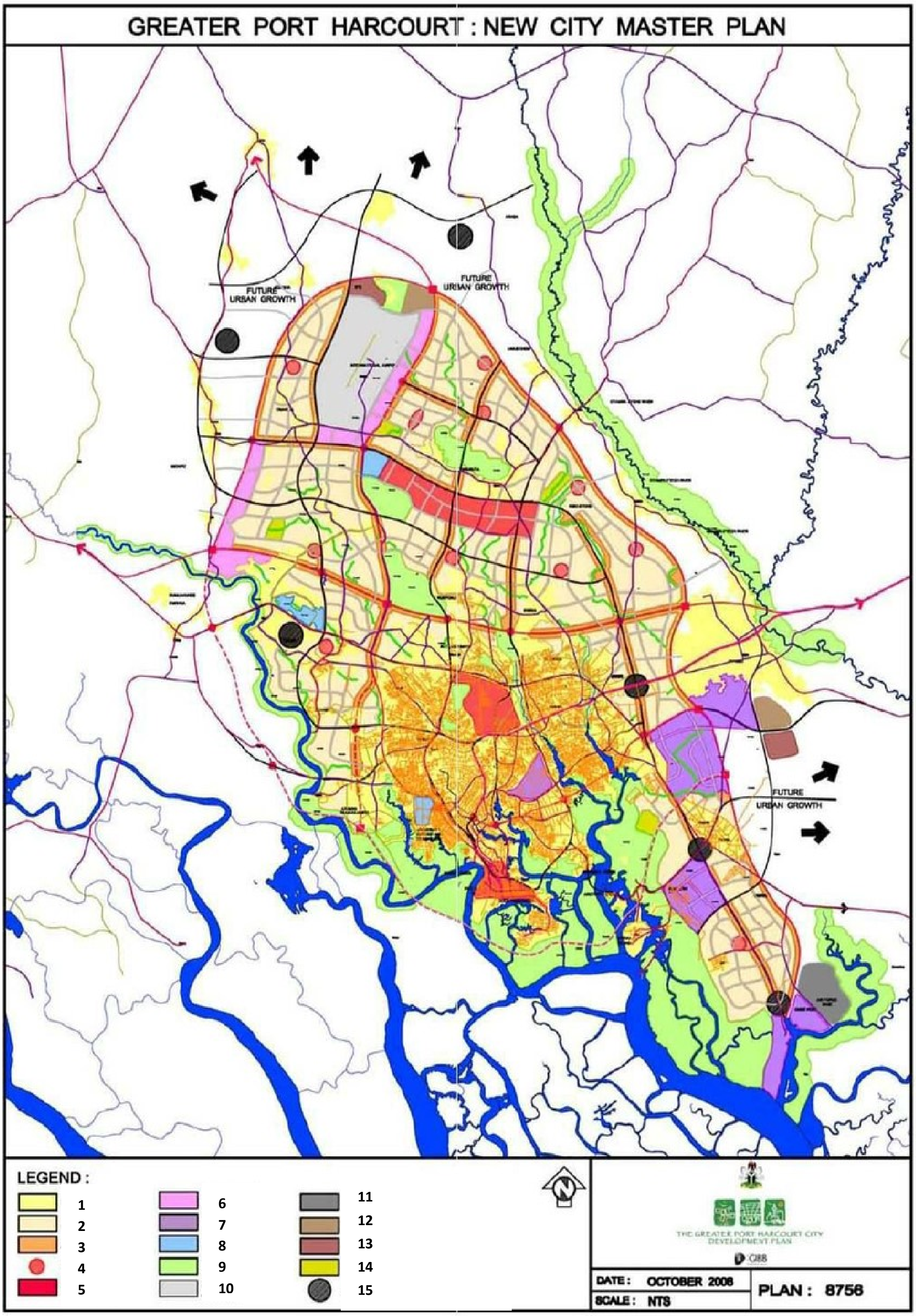


Figure 3.21 Layout of the Greater Port-Harcourt Masterplan. Legend of Land-uses shows 1-Built-up Area, 2-Neigbourhood general, 3-Arterial road, 4-District nodes, 5-Central spine/metropolitan node, 6-Commercial /light industrial, 7-Industrial, 8-University, 9-Open space/Riverine, 10-International airport, 11-Airforce base, 12-Dump site, 13-Cemetry, 14-Golf course, 15-Regional nodes.

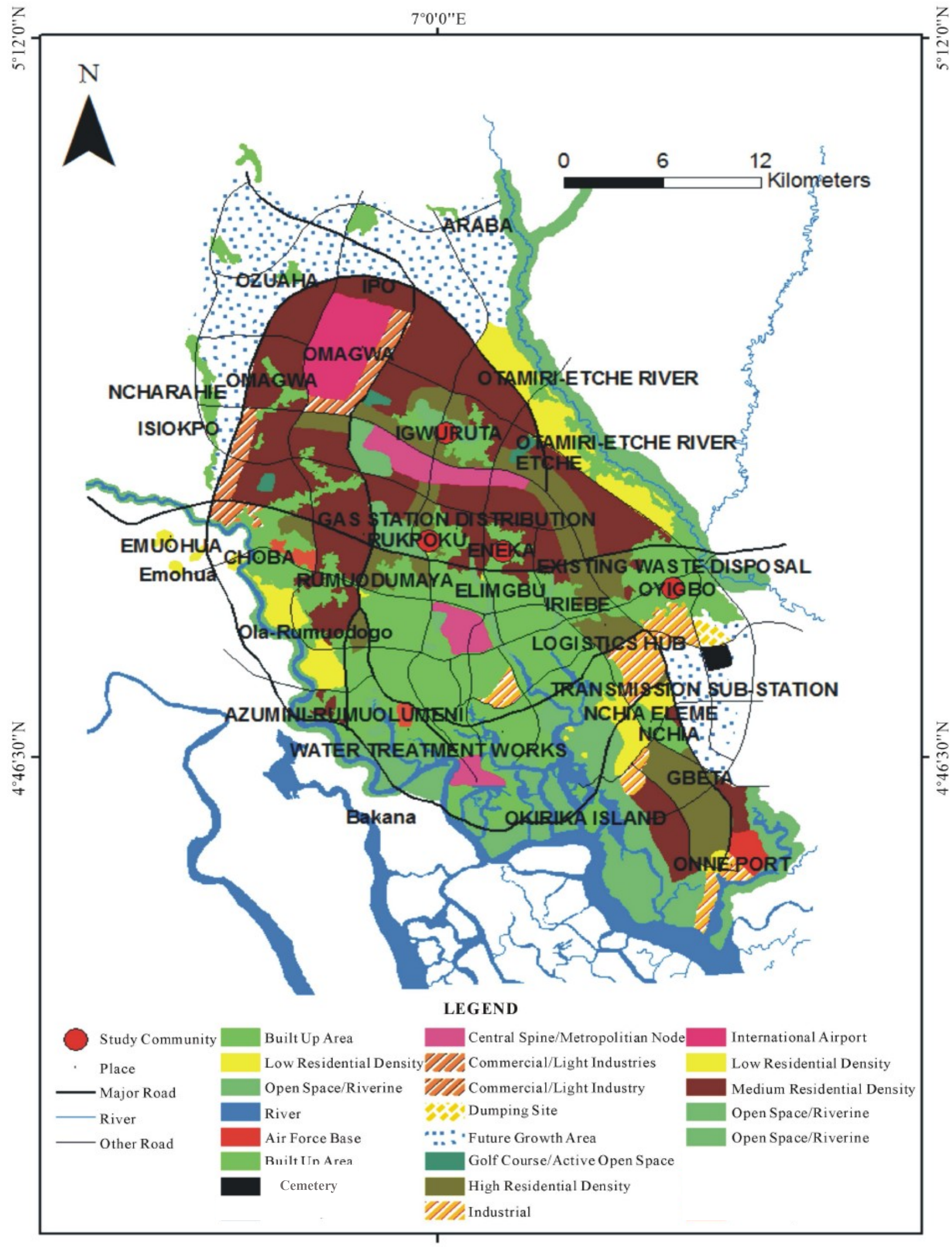


Figure 3.22 The holistic Greater Port-Harcourt Master Land-use plan comprising of Built-up areas; Residential areas including high, medium and low residential density areas; Industrial areas including commercial/industrial area; Cemetery; Dumping site; International airport; Universities; Open spaces including riverine areas, golf courses; Rivers; Central/ metropolitan node; Roads including major, minor and other roads as well as future growth areas. Source: GPHCDA (2008).

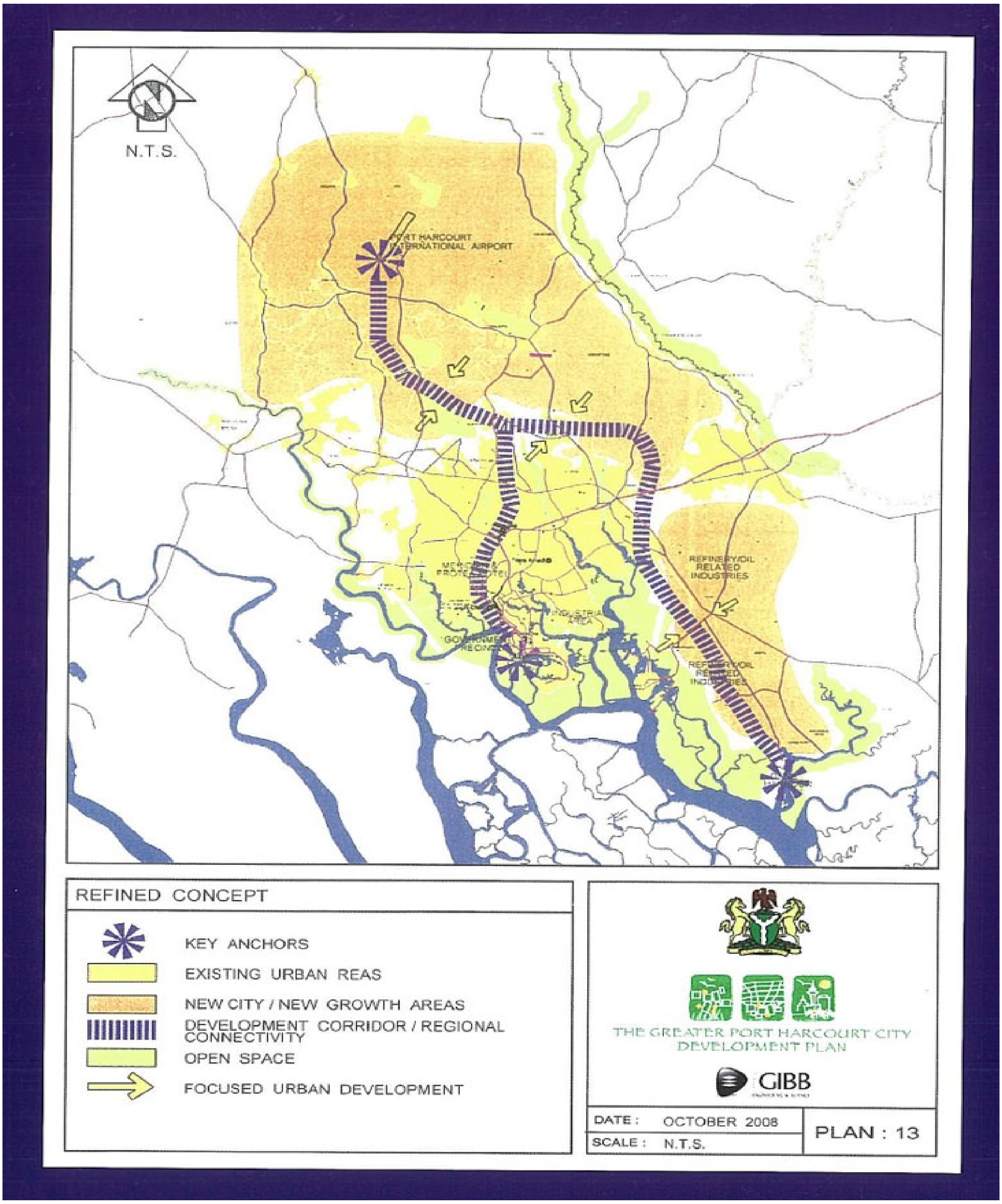


Figure 3.23 Map of Greater Port-Harcourt showing growth areas, and key anchors. Existing and new city in the Masterplan (GPHCDA, 2008).

The comprehensive Masterplan comprises of Land-use Masterplan and other sectoral Masterplans (Table 3.2). Implementation of the entire Masterplan is to be done in phases, commencing from Phase-1 through Phase 2 to the Phase-3 project (Figure 3.20). Phase-1 layout is located in the Northern axis of the Masterplan near the Port-Harcourt International Airport and is sub-divided into four manageable sub-phases A, B C and D. \phase-2 layout is located in the Eastern axis near Etche LGA, whereas Phase 3 Project is located in the South-eastern part of the Masterplan near the Onne Seaport at Eleme. All phases will be connected by the Priority Road (M1 North-South Link Road), which is a dual carriage freeway (ERML, 2009). The main anchors are Onne Seaport, Port-Harcourt Harbour and the Omagwa International Airport (Figure 3.23).

Generally, the layout consist of built-up areas including High, medium and low density residential areas; Commercial and industrial areas; Cemetery; Dumping site; International airport; Universities; Open spaces including Riverine areas, Golf courses, Parks, Gardens with luxuriant landscape elements; Rivers; Metropolitan node; Roads including major, minor and other roads as well as Future growth areas (Figure 3.21 and 3.22). Facilities include 24 hours electricity supply infrastructure; a network of good roads/streets and public; transportation system; drainage and storm water management system; engineered sanitary landfill for solid waste disposal; surveillance; and efficient security systems among other things (ERML, 2009; GPHCDA, 2010).

Table 3.2 Table showing the Sector Masterplans and Sub-Masterplans of the Greater Port-Harcourt City Development (ERML, 2009).

Sector Masterplans	Sub Masterplans
Land Use Masterplan	
Transportation Masterplans	Roads Masterplan
	Public Transport Plan
	Freight Transport
Water Masterplan	
Waste Water Masterplan	
Storm Water Masterplan	
Energy Masterplan	
Integrated Waste Management Plan	
Social Services Infrastructure Masterplan	

3.6.2 Phase-1.

Phase-1 in 2017 is at the construction stage of the project cycle and is expected to be completed by 2020. As shown in Figure 3.24 and 3.25, Phase-1 layout covers 1,692.07HA (16.921km^2), extending from the Port-Harcourt International Airport junction across to Professor Tam David-West Road to part of Igwuruta. The ongoing project layout comprises of clusters of neighbourhoods including Low, medium and high-density residential area, mixed-use complexes, schools, churches, golf course and estates. Other land uses include storm water drains. Moreover, the GPHCDA have planned to build 30,000 housing more units during this phase (ERML, 2009; GPHCDA, 2010).

The project cycle for the entire Phase-1 includes Planning, Preliminary Design, Consent, Detailed Specification and Tender, Procurement, Construction, Operation and Maintenance stages (GPHCDA, 2010). The Government has taken the responsibility to build the bulk infrastructure, but would rely on the private sector and individuals to build the commercial and housing units, however, the developments will be controlled and approved under a planning permit system. Moreover, the planning and construction of bulk infrastructure were projected over a period of 36 and 48 months from 2009, but, completion of this phase has been delayed by financial, administrative and political factors such as change of government administration, removal of top GPHCDA staff, limited funding for the remaining part of the Phase-1 project (Ebiri, 2016). In 2015, the new administration had set a 5-year target for the completion of the entire Phase-1 (Ebiri, 2016). Financially, the construction cost of the bulk infrastructure of Phase-1A was estimated at \$1.6Billion US Dollars, while the whole Phase-1 was estimated at \$2.5Billion US Dollars (GPHCDA, 2010).

3.6.3 Phase-1A.

Presently in the construction stage of the project cycle, Phase-1A development covers a landmass of between 723 and 750 hectares (7.23 and 7.50 km^2) and is situated east of the International Airport (GPHCDA, 2008, 2010). The site is bordered on the west by the Prof. Tam David-West (M1) road, on the north of Port-Harcourt by the Owerri Road, on the south-east by Igwuruta and to the north-west by Omega (GPHCDA, 2010). As shown in Appendix 3.5 the project activities covered under Phase-1A include the construction and operation of: A 132kV double circuit transmission line; A 132/33/11kV 100MVA substation; bulk water abstraction, storage and supply system; priority road and internal street network; construction of a sewage treatment plant and its associated reticulated pipeline network; a sanitary engineered landfill waste disposal facility to service the New City; 3,000 houses (housing estate with internal services consisting of: internal roads; sewage, drainage and storm water system; power reticulation system; solid waste handling facility; potable water reticulation system) (ERML, 2009; GPHCDA, 2010). The Phase-1A project activities include construction and operation of the New Rivers

State University of Science and Technology (2.12 km^2), Sports precinct (0.5 km^2) in addition to the 1,000-bed mega hospital complex. Appendix 3.5 shows an overview of the project activities for the Phase-1A Development. ERML (2009)

At present the Phase-1A projects completed include:

- The water supply project
- The Sports precinct, including the 18 hole Golf Course, basket court, volleyball, handball court, Gym, Squash court, Indoor sports hall
- 1000 Bed Mega-hospital, etc.

Table 3.3 showing the Project Schedule of the Phase1-A project, ERML (2009).

Project	Time frame (weeks)
Power Generation and 33KVA Transmission	24
Access road	16
Stormwater canal	16
Priority Roads (M10)	120
Package Waste Water Treatment Works (PWWTW)	50
Temporary Water Supply	72
Internal Township Services	50

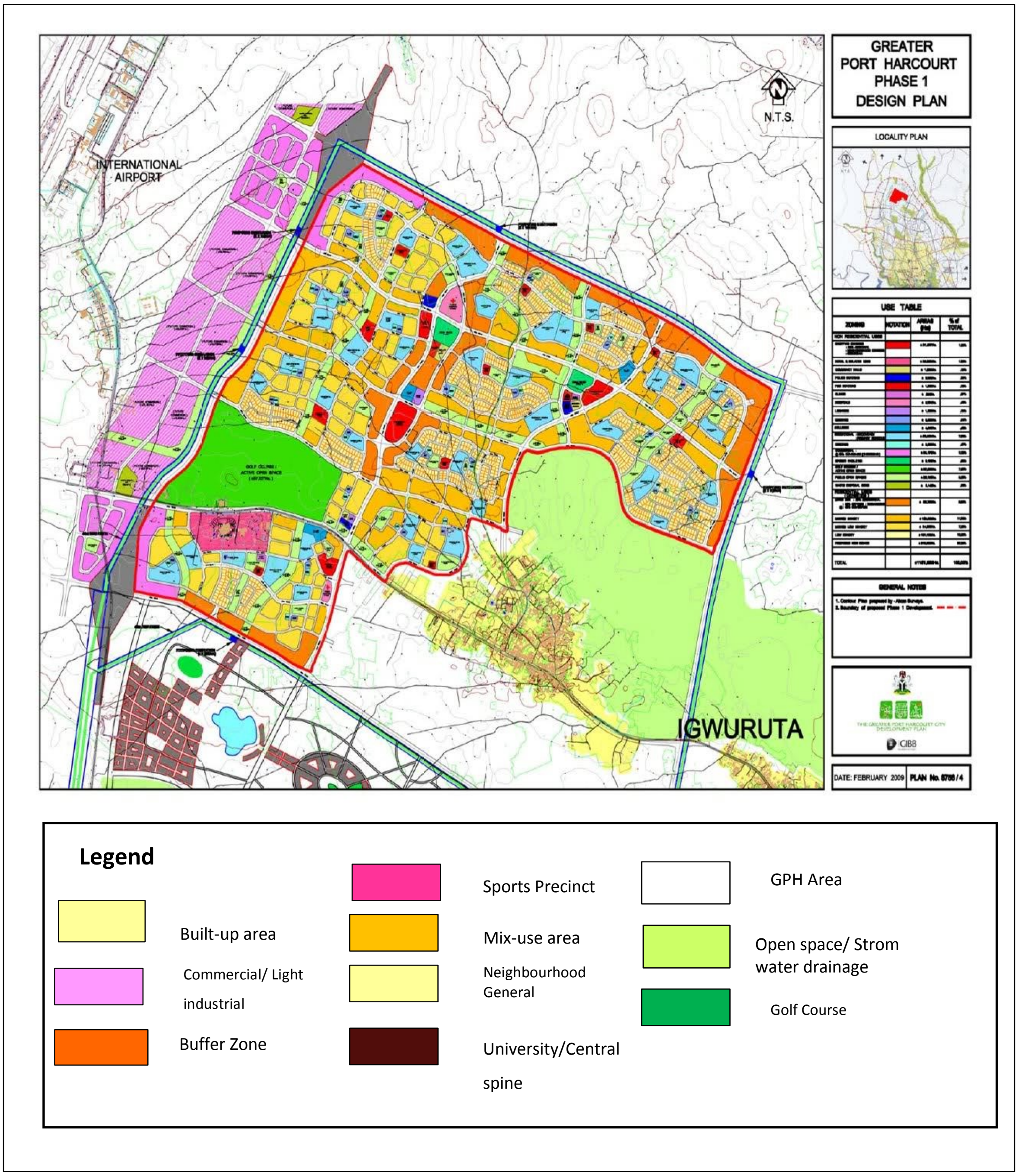


Figure 3.24 Phase-1 layout showing 1A, 1B, 1C and 1D sub-projects (Gibbs, 2016).

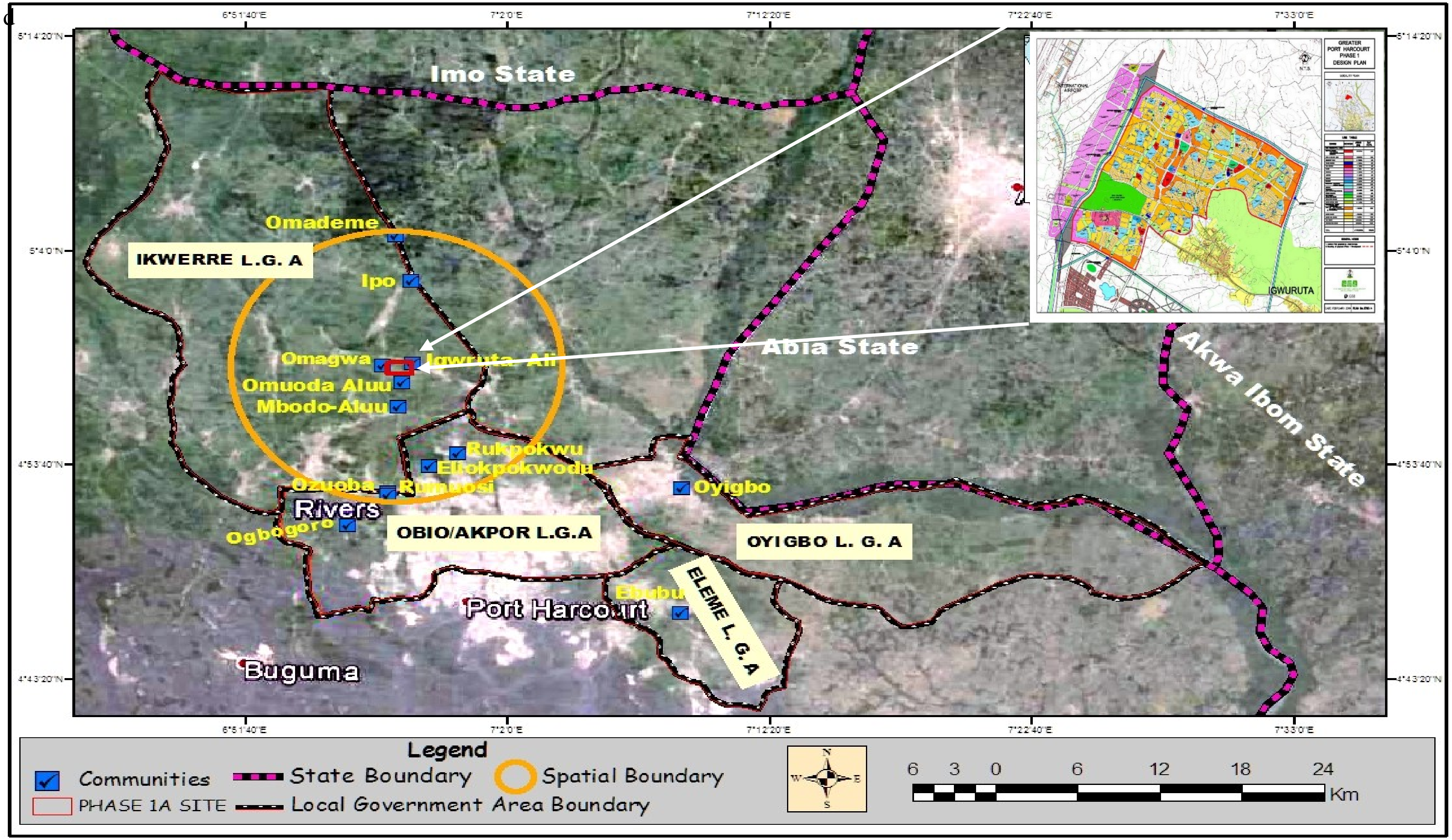


Figure 3.25 Map showing the location of Phase-1 development within Greater Port-Harcourt (GPHDA, 2008).

3.6.4 Project Justification.

As stated in subsection 3.2.2, in 1912, Port-Harcourt was established with the town and country planning system during the British rule to manage its urban composition and population growth (ERML, 2009; Owei et al., 2010; Ede et al., 2011). Up until 1960, the Old City was regarded as well-developed and well-managed, and earned the status of a 'Garden City'. The term Garden City was adopted from the British planning system with the aim of a developing a planned and decentralised network of cities as an alternative to the squalor of the Victorian urban concentration system (Ratcliffe *et al*., 2004). The concept of Garden City was a reaction to the squalor of the Victorian system, just as the pursuit of sustainable development today is a response against environmental degradation (Ratcliffe et al., 2004). Similar to the Garden Cities in Britain, the old Port-Harcourt city was equipped with good infrastructure and service delivery, low densities, well-defined institutional precincts, well maintained open spaces and parks, and a formal central business district (CBD) (Ede et al., 2011).

Today, some authors have questioned whether the appellation 'Garden City' is appropriate for the city due to the disconnect of important features in the city (Obinna et al., 2010; Owei et al., 2010; Ede et al., 2011; Wizor, 2014). Nigeria gained independence since 1960 and experienced 30 years of military rule. During this time, established planning laws and systems were neglected. As highlighted earlier, this period also witnessed the discovery of oil and gas, and the proliferation of petroleum activities led to major population influx into the city (Ede et al., 2011). Lately, a status-quo assessment performed by the government revealed several problems facing the city. Table 3.4 highlights some pertinent issues. The commonly held view was that of a need to reinstate the value and status of the city (GPHCDA, 2008; Obinna et al., 2010; Owei et al., 2010; Ede et al., 2011; Wizor, 2014). The primary justification for this project was premised on the overarching need to transform Port-Harcourt City into a mega-city, to eventually eradicate slums, to enable safe and healthy living conditions, and provide employment opportunities (ERML, 2009).

Table 3.4 Urbanisation related problems in Greater Port-Harcourt city, Source: ERML (2009).

Problem type	Explanations	Needs
Improperly planned developments	Urban sprawl with poor service delivery accompanied rapid population and urban expansion due to the oil boom.	There is need for planned and controlled developments in the future starting with the housing estate and other developments in Phase-1A
Settlement pattern/ housing	Housing in Port-Harcourt varies, ranging from high modern to low-income squatter settlements. The majority of houses falls into the middle to low-income category reflecting the city's socio-economic status. There are over 30 neighbourhoods in the city and 13 squatter settlements, which comprise of 30,000 dwelling units that harbour as many as 275,000 people. These areas were not formally planned or developed, and as such the services, facilities and sanitation are poor	There is need to accommodate approximately 350,000 households.
Topography/ drainage system	The Old Port-Harcourt City is naturally a very flat terrain complicating storm water management and performance of drainages. Moreover, the existing drainages are inadequate and very ineffective. Hence depression storage of storm water and persistent flooding is a common phenomenon.	As stated in the plan, there is a need to provide a reticulated drainage system and well planned/designed storm water system for the new city.
Traffic	Traffic congestion at present is often a problem	There is the need to construct major and minor roads
Electricity	The power supply in the old Port-Harcourt City is grossly inadequate and has a significant impact on its economy and growth potential.	There is a need to construct a double-circuit transmission line and a 132/33/11kV 100MVA Sub-station in advance to provide 24 hours uninterrupted power supply in the proposed new city.
Solid waste management	There is no formal solid waste collection system and disposal facility in place in the city. Environmental sanitation is indigent. The potential for the contamination of surface and groundwater resources by open dumping of solid waste in the city is high	There is a need to systematically put a reticulated sewage pipeline system and treatment plant in place over time for the new city. Moreover, there is a need to construct wastewater treatment plant and sanitary landfill and solid waste disposal facilities
Water supply	Water supply and distribution infrastructure in the old city are poorly developed. Therefore domestic water supply is inaccessible to many people.	There is a need for planned bulk water abstraction, storage and supply system.

3.6.5 Environmental Sustainability.

Sustainability is a well-known concept in River State. It forms the basis upon which EIA is carried out in the State and Nigeria as a whole. After the decision to implement the Masterplan, an EIA study was performed for the Phase-1A project on behalf of the GPHCDA by Environmental Resources Managers Limited (ERML) consultancy firm. Two volumes of the EIS covering a range of Phase-1A subprojects were produced (see Table 3.5). The EIA study was used to integrate the sustainability requirements into implementation of Phase-1A projects of the GPH Masterplan (ERML, 2009). The EIA study conducted between 2008 and 2009 was basically used to assess the potential and associated impacts of the proposed Phase-1A sub-projects of the Masterplan, and to recommend mitigation measures for negative impacts. The study covered the Phase-1A project area, and not the entire City (ERML, 2009). By implication, it means the watershed scale impact of the Masterplan on hydrology may not be fully understood.

Table 3.5 Stages of the Phase-1A development and approaches to realising sustainability, Source: ERML (2009).

Stage	Approach to ensuring sustainability
Planning stage	Submission of EIS and EMP to NESREA
Construction stage	Compliance monitoring based on EMP report
Operation stage	Periodic monitoring and environmental auditing based on the EMP

According to ERML (2009), the GPH Phase-1A project was proposed with due consideration for environmental sustainability. The GPHCDA's take was that an environmentally sustainable project must preserve a stable resource base, avoid overexploitation of renewable resources and preserve biodiversity (ERML, 2009). Three stages were involved namely: planning, construction and operation stage (Table 3.5).The objectives were to recommend mitigation measures, to minimise potential effects from certain aspects of the development, and to maintain sustainability using an environmental management system (EMS) to be put in place

(ERML, 2009). Table 3.6 below shows the various stages of the development process and approach to ensuring sustainability.

Table 3.6 showing Phase-1A main activities covered in the EIS report summary.

Volume One of Phase-1A EIA Report covers the construction of the following sub-projects:
1. 132kV double circuit transmission line;
2. 132/33/11kV 100MVA Substation;
3. Housing estate, underground electricity transmission and distribution cable network;
4. Installation and operation of a standby Generator and its Fuel System;
5. Bulk water abstraction, storage and supply;
6. 8km road network;
7. Housing estate internal roads,
8. Drainage and storm water system.
Volume Two of Phase-1A EIA Report covers the construction of the following sub-projects:
1. A sewage treatment plant;
2. Associated reticulated sewage transmission pipeline network; and
3. A landfill waste disposal facility.

In the EIS report, it was concluded that the Phase-1A development would provide the following benefits, including an increase in income from transportation; an increase in income from employment; increased trade of local and national commodities; skills acquisition and training of workers from local communities; improved access from roads; improved quality of life; better social inclusion. Conversely, the report also emphasises that the project would generate several adverse effects including influx related impacts, impact on transportation, impact on vegetation and wildlife, physical displacement, and impact on groundwater, impact on surface water, noise and air pollution impacts, increased solid and liquid wastes (ERML, 2009). Attention was also drawn to the impact on surface water, but due to the scope of the study, the assessment of hydrologic impact was limited in the sections given to the author and could be limited in the fuller report given the area of Phase-1A.

The Phase-1A and Phase-1 project area span 7.6 km^2 and 19.2km^2 respectively, but the entire GPH area cover approximately 1900km^2. Despite the weak emphasis on the potential increase in flooding, assessment of the effects of Phase-1A or Phase-1 development on flooding in the watershed should not be limited to local or subbasin assessment. Some hydrologic studies have demonstrated that the effect of urbanisation is greater in small basins and conversely negligible in larger basins (Leopold, 1968; Hollis, 1975; Brooks, 1985; Booth, 1991). Hence, there is a need for improved understanding of the effects of urbanisation on the entire watershed beyond the GPH project areas, given that there is no knowledge of watershed scale impact due to urbanisation on flooding in the area.

Moreover, studies have also suggested that the location or placement of a development within a basin in the watershed can have significant influence of watershed hydrology (Mejía and Moglen, 2009; Su *et al.*, 2014; Du *et al.*, 2015). The basins casing the Phase-1A and the entire Phase-1 development are located upstream compared to the majority of basins downstream in the catchment. Du *et al.* (2015) showed that an increase impermeable surface (IS) upstream increased peak discharge approximately 14 times more than the same increase in the impermeable surface downstream in the Longhua Basin, China. Understanding the spatial variation of IS's impact on runoff can help locate suitable locations for urban development (Mejía and Moglen, 2009; Su *et al.*, 2014; Du *et al.*, 2015).

3.6.6 GPH Development Alternatives.

During the planning stage, five main alternatives were examined for the Phase-1A subproject including the: No-project alternative, Delayed project alternative, Alternative location, and Urban renewal and Current project. Green Technology, Wastewater treatment alternatives were other sectoral options. Selection of the major alternatives was based on the: desirability/acceptability of the project, government's position on the project, as well as the socio-economic and cultural impacts of the project (ERML, 2009).

No-Project alternatives.

The No-project alternative meant that the project would not go on. From the EIA report, this alternative is possible when the costs outweigh the socio-economic benefit ERML (2009). However, the proponent also considered that this alternative would result in loss of time, money and effort invested in the pre-planning design, engineering and feasibility study activities. Therefore, the alternative was rejected. It was also excluded because the socio-economic and cultural impacts were positive and that the negative impacts could be mitigated (ERML, 2009).

Delayed Project Alternative.

The delayed alternative was considered based on the notion that planning and development activities could be stalled if conditions were not favourable. Stalling the project could be due to civil unrest, or if public opinion was against the development due to perceived adverse socio-economic and cultural impacts. However, these were not the case. It was reported that the timing and public opinion were favourable (ERML, 2009). The project was carried out in the absence of civil unrest or war. Based on these reasons, the delayed project alternative was not selected

Alternative Location.

This alternative was an important component of the project planning process. Consideration of the location alternative was based on planning, and economic factors such as availability of land, the commitment of available space to other land-uses, the proximity of open space to the old city and financial cost. Supplementary locations considered for the Phase-1A project included Omoku/Ogba area north-west of the old city and Bori area situated south-east of the old city. Both locations were found non-contiguous to the old Port-Harcourt City. According to ERML (2009) these places are several kilometres away from the old City. From a planning standpoint, these alternative locations were disallowed due to the huge financial cost and resources required to construct an entirely new city. Again, those options was not selected because they are not contiguous to the old city (ERML, 2009).

Urban Renewal of the Old Port-Harcourt City.

Urban renewal of the old city involved the enhancement of the physical and social infrastructure of the urban areas (ERML, 2009). It involved the significant construction of new structures and demolition of old structures. This option was excluded because of the major disruptions to daily socio-economic activities it would have caused during the construction stage. Factors considered included the potential increase in traffic congestion, the rate of accident, conflicts and other socio-economic problems (ERML, 2009).

Green Technology.

Rather than Electric Energy, the use of Solar Energy was preferred as a greener means of power generation. This alternative was included to provide power for some utilities such as perimeter lightings, street lightings and other domestic uses. This alternative was considered due to climate change awareness and green technology advocacy (ERML, 2009).

The Current Project Alternative.

The current project alternative was the preferred option. Compared to other alternatives described above, the site selection was based on economic and planning criteria such as:

proximity to the old city; availability of land; the size of land, the potential value of development due to proximity to the old city. Again, the location was neither a forest reserve nor a conservation area. Moreover, the current project location was preferred because the current project location would maximise economic benefits (ERML, 2009). This suggests that the main justification for this alternative was based on the economic, planning and the environmental context. However, the environmental consideration was related to conservation and not related to the hydrologic sensitivity of the watershed.

Consideration of alternative was an essential part of the Phase-1A project planning process. As stated above the justification for the final choice and exclusion of other alternatives were mainly based on economic and planning considerations. In the Institute of Environmental Management and Assessment quality mark article, EISs should: contain the assessment of “Do nothing or No project option, and explain reasons why the other alternatives have not been selected. Sadler (1996) argues that EIAs should compare location and technology alternatives to determine the most environmentally-friendly or of best practicable environmental option (BPEO). Glasson *et al.* (2013) further emphasised that the preferred location alternative should be based on the need to maximise economic, planning and environmental benefits. In this case, although the No project alternative as well as the justification of final choice were stated, however, the justification was not mainly based on the sensitivity of the watershed. Instead, the main reasons were limited to a land value, proximity to existing city and the protection of forest reserves.

The identification, analysis, and comparison of alternatives to the proposal is the key to creative, pre-emptive and decision-relevant assessment (Sadler, 1996). According to Glasson *et al.* (2013), various location alternative are likely to generate different effects in the environment. The decision to locate Phase-1A project anywhere within the watershed is expected to alter the magnitude of runoff due to decreased increased IS. From a hydrologic standpoint, it is uncertain whether the location of the current project is the least disruptive. The next chapter describes the methodology of the study.

Chapter 4. Research Methodology.

4.1 INTRODUCTION.

This chapter describes and justifies the general research design, workflow and methods applied. The goal was to provide a clear and complete description of the research process. Section 4.2 presents the research approach, which provided details of the type and nature of the research. Section 4.3 described the general framework of the study consisting of the workflow. Subsequently, section 4.4 described the data and justified the process and methods of data collection. It provided information of when, where, and how the data was collected. Next, section 4.5, the Methods and Procedure section described the available methods and also justified methods and procedures followed in the study. The procedural aspect provided a detailed description of steps taken for the data processing, model run, and calibration in addition to validation in this study. Section 4.6 described methods and procedure used for studying LULC Change detection. Next, section 4.7 describes the procedures and assumptions made in the application of alternatives and construction of future scenarios. Section 4.8 presents the procedures used in the preparation of topographical and spatial input data. Section 4.9, describes the runoff estimation using hydrologic modelling technique, while section 4.9 also describes the flood inundation analysis using hydraulic modelling and mapping techniques. Lastly, section 4.11, the data analysis section described the statistical tests used to analyse results.

4.2 RESEARCH PROJECT APPROACH.

This study is a hydrology and global environmental change research that combines quantitative, correlation, prediction, simulation and case study approaches to address the research questions. Philosophically, the research adopts a positivist paradigm, because it was conducted from an objective standpoint. Positivists believe that reality can be observed and studied from an independent standpoint, without interfering with the phenomena being studied (Gray, 2013). This study combined a number of quantitative approaches in generating numerical data, after which it was subjected to rigorous quantitative and statistical analysis in an objective manner. Quantitative approach was adopted firstly, because the flood phenomenon could be quantified (Kothari, 2004). Secondly, this type of research attempts to maximise the objectivity, replicability, and generalisability of findings and is concerned with prediction (Harwell, 2011).

Correlation approach was also used because several dependent variables (e.g. runoff, water surface extent) and independent variables (e.g. rainfall, land-use changes) were examined. Moreover, correlational approach uses statistical measure of association to measure the relationship between different variables in the study (Clarke, 2005). The simulation and prediction approaches were adopted because the relationship of the variables are known. In this study, the effects of the independent variables on the dependent variable were predicted using certain parameters (e.g. Peak discharge and flood depth). Prediction approach is used when the relationship of variables or phenomena are already known and an attempt is made to predict the possible behaviour or event (Clarke, 2005). A desk-based simulation research was conducted because of the nature of the research. Much of the study was done away from the study area using computer-based modelling and geographical information system (GIS) techniques to examine the behaviour of the hydrologic system of the study area.

Finally, for in-depth understanding of the effects and behaviour of the Greater Port-Harcourt context a case study approach was used.

> *A case study is an empirical inquiry about a contemporary phenomenon (e.g., a "case"), set within its real-world context—especially when the boundaries between phenomenon and context are not clearly evident (Yin, 2009a:18).*

This approach was adopted because of the purpose of the research which is, in other words, was to gain an in-depth understanding of the future catchment response to urbanisation (and climate changes) in the Greater Port-Harcourt area. Stake (1995) suggested that a case study provides a mode of inquiry that enables in-depth examination of a phenomenon and is applicable whenever the opportunity to learn is of primary importance. In this study, the interest was to understand the catchment response to natural and human disturbances. In terms of application, Yin (2011) added that case studies are crucial when studies (such as this) address either a descriptive question—what will or is happening or has happened?—or an explanatory question-how or why did something happen? In this study, both forms of questions were addressed. Johansson (2003) argues first, that case studies should have a case i.e. the object of study. Second that the case should, be a complex functioning unit and be investigated in its natural setting with a combination of methods. In addition, it should be contemporary. Generally, case studies capture the complexity of a single case. It utilises a combination of methods for answering questions in this study. This study combines a number of methods mainly spatial analysis, scenario analysis, hydrologic modelling, hydraulic modelling in addition to flood hazard and damage potential mapping to address the different research questions.

4.3 GENERAL RESEARCH FRAMEWORK

The main procedures followed in this study can be framed under six main stages as presented in Figure 4.1. They include (1) Land-use/Land-cover change detection analysis, (2) Digitisation of Masterplan and application of alternatives and scenario construction, (3) Spatial and topographical data preparation (4) Hydrologic or rainfall-runoff modelling (5) Hydraulic or river network modelling (6) Flood hazard & damage potential mapping.

First, LULC change detection analysis was conducted using Landsat satellite images (with a ground resolution of 30m x30m) and land-use polygon maps to estimate historic LULC changes for three time periods 1986, 1995 and 2003. The objective was to compare historic LULC changes with potential future changes. Generally, the LULC change analysis in chapter 5 involved data acquisition, data pre-processing supervised classification, accuracy assessment and change detection analysis.

Second, the entire GPH Masterplan and its Phase-1 location alternative were digitised from a hard copy map. The reason for this was to estimate the effects of future changes to land-use on flooding due to climate change and the implementation of the Masterplan. This resulting land-use change was assumed to reflect future LULC changes by 2060. The objective of the latter was ultimately to compare the effects of the different Phase-1 location alternative on flooding because, “location alternative are particularly relevant in a change of land use applications” (DEAT, 2004:5). Scenario of plausible changes in LULC and climate was also developed. Forest scenarios include: No forest (NF), Urban Masterplan (UMP), Urban Masterplan + urban sprawl (UUMP) scenario, Low afforestation scenario (LAF), and High afforestation scenario (HAF) conditions, while U1 and U2 are historical urbanisation scenarios compared in this study. Moreover, three climate scenarios were compared consisting of 44yr (A1B), 57yr (A2) and 100yr storm return periods. The LULC scenario was conducted to check the effects of the Masterplan and urban sprawl on flooding. The urbanisation and afforestation scenarios were constructed to understand the watershed’s response to urbanisation and afforestation. Meanwhile the climate scenarios were used to examine the watershed response to afforestation under increasing storm conditions.

Third, topographical and spatial data derived from the LULC change detection analysis were subsequently processed as inputs for hydrologic and hydraulic modelling. For topographic data, the Shuttle Radar Topography Mission (SRTM) 90x90m resolution digital elevation model (DEM) was obtained. Two DEM map tiles (38_11 and 38_12) were initially merged, clipped and later re-projected from WGS84 geographic projection to WGS84_UTM_Zone_32N projected coordinate systems. Data processing was done using ArcMap version 10.1 programs. HEC-GeoHMS and Arc Hydro geospatial extensions in ArcMap were then used to delineate sub-basins and streams from the DEM. They were also used to extract channel characteristics such as slope, flow paths, centre points and reach lengths etc.

Spatial data, primarily consisted of LULC and soil maps. Hence, historic and future LULC maps were used to generate spatial date inputs for flood modelling (See section 4.9). In the hydrologic model, LULC maps were used to generate percentage impervious surface (PctImp), Curve number (CN) and Manning's N roughness coefficient data. Hydrologic and hydraulic models use these data as basic inputs for modelling. For CN generation, soil map and LULC maps were integrated. The NRCS-CN is an index that represents the runoff potential of a sub-basin. Ultimately the CN number was determined from the combination of LULC maps and soil hydrologic group (HSG) maps. During the spatial data preparation in this study, there was no readily available soil map for determining HSG, therefore a 1:1,000,000 digital map was adopted from the United Nation's Food and Agricultural Organisation (FAO). Soil map was re-classified (based on their soil texture and antecedent moisture content) into four hydrologic soil groups (HSGs) A, B, C and D. Note, the runoff potential increases from A to D).

Fourth, hydrologic or rainfall runoff modelling was performed in Chapter 6 using Hydrologic Engineering Centre's Hydrologic modelling system (HEC-HMS). HEC-HMS and HEC-GeoHMS in ArcMap used for hydrologic simulation were developed by the US Army Corp of Engineers (USACE) (Feldman, 2000). The model was used for simulating rainfall-runoff and routing processes in dendritic watershed. The modelling was performed for 5 basins and 37 subbasins. The goal were to estimate past and future effects of the LULC and climate changes on catchment hydrology, whereas hydraulic modelling in Chapter 7 was performed to determine the changes in flood depth, extent and velocity in the area.

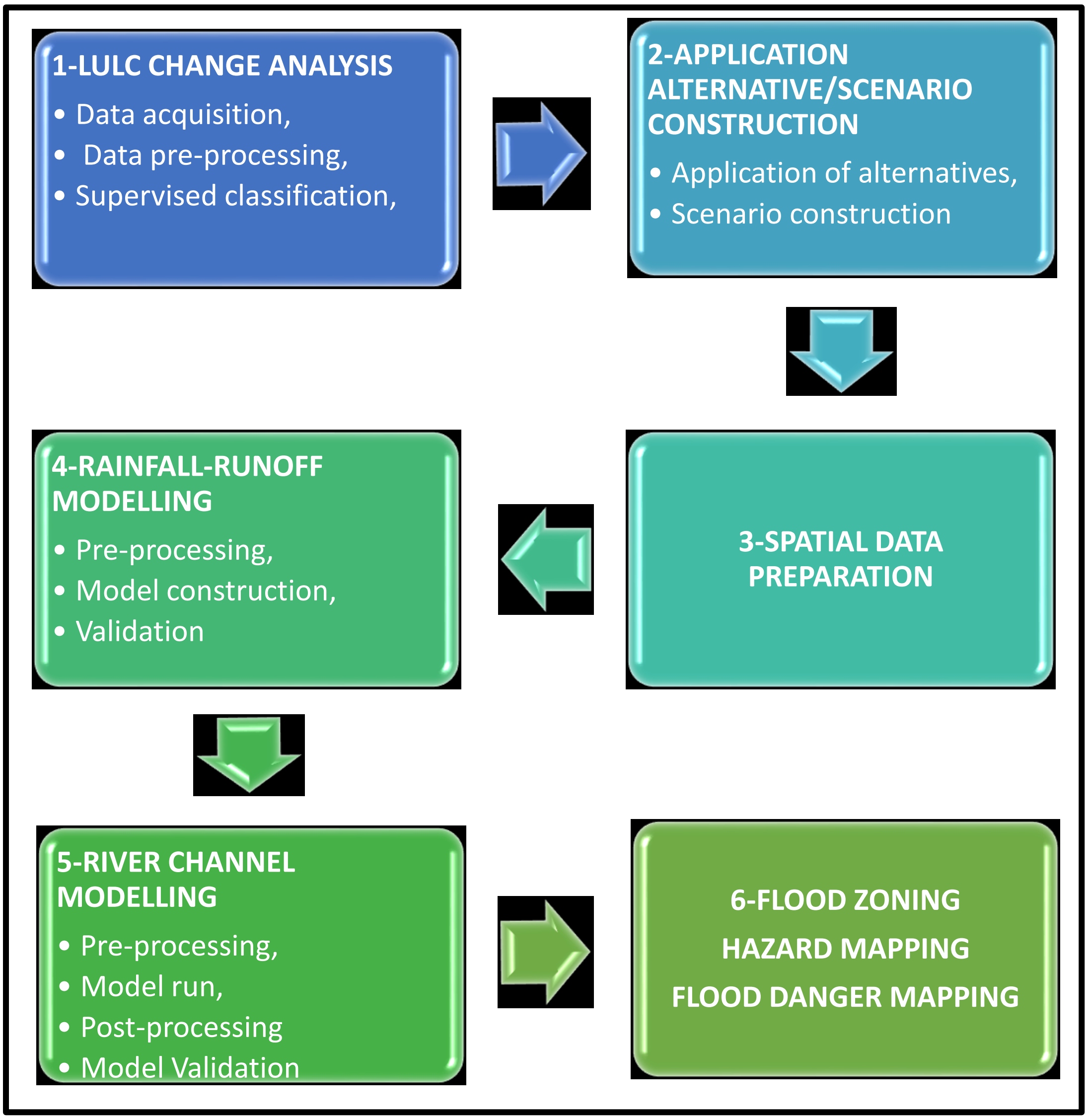


Figure 4.1 General framework of study involving six (6) main stages, including: (1) Land-use/land-cover change analysis (2) Screening of alternatives/scenario construction (3) Spatial data preparation (4) Hydrologic modelling (5) Hydraulic modelling (6) Hazard mapping, flood danger mapping and zoning.

The goals for using hydrological modelling were to: (a) estimate historic effects on hydrologic parameters. (b) estimate future affects hydrologic parameters due to the implementation of the entire Masterplan. (c) compare the effects of the three location on flow peak discharge. As shown in Figure 4.1, HEC-HMS outputs in this study were used as data inputs in the River Analysis System model. Fifth, the river channel system was modelled using HEC-RAS version 4.10. The 1-D hydraulic model integrated with ArcMap was used to perform one dimensional steady state analysis for estimating water surface profile (WSP), flood extent and velocity. The goals were to: estimate past and future effects of LULC and climate change on flooding. Sixth, flood hazard mapping was performed to visualise the potential flood effects. This was used for flood zoning and mapping damage potential. It was also used to identify priority infrastructure for flood risk management.

4.4 DATA COLLECTION.

Data collection for this study was aimed at understanding the effects of urbanisation and climate change on flooding. Although *primary* data were initially collected, this study mainly used secondary data collection methods, *Primary data* are original data collected first time, while *secondary data* refer to data that are already available which have been collected and analysed by someone else (Kothari, 2004). In terms of primary data, photographs of Phase-1A development activities and environment were taking during site visit on the 10th and 11th of August 2012. This method was used to observe and provide first-hand evidence of the project activities and the state of the receiving environment (See Appendix 4.1). It was also used to provide first hand evidence of local land-use change issues in the area already. The main benefit of this method is that it eliminates bias, when done properly. In terms of secondary data collection, published and unpublished data sources were used as shown in Table 4.1.

Published data acquired consist of: (1) LULC thematic mapper (TM) and Enhance thematic mapper (ETM+) satellite imageries for change detection analysis as well as flood modelling. (2) Shuttle Radar Topography Mission DEM covering the study area was also obtained for delineating channel characteristics and elevation; (3) Future rainfall scenario data from McSweeney *et al.* (2010) was sourced for hydrologic modelling; (4) Soil data from the Food and Agriculture Organization of the United Nations was used for determining hydrologic soil groups and runoff potential; (5) Historical peak discharge data was used for validation and was from a published work by Okoro and Uzoukwu (2013); Unpublished secondary data used include: Observed daily rainfall data from the Nigerian Meteorological Agency (NIMET) for hydrological modelling; Historical LULC polygon map from the River State Ministry of Land and Housing (Riv-MoLH) for HMS modelling and estimating changes; Future Masterplan and layout maps as well as the EIS document from GPHDA (Table 4.1).

Table 4.1 Details of data collected for study. Historical and Future LULC data, Elevation data, Soil data, Historical rainfall data, Rainfall scenario data and Flood mapping validation data.

Data	Type of data	Source	Published?	Date acquired/prepared	Year/Period covered	Entity ID/Reference	Location in thesis
Historical LULC data	Landsat 5 TM and Landsat 7 ETM+ (Remotely sensed land-cover satellite imagery)	USGS	Yes	19-Dec-86	1986	LT51880571986353XXX10	Figure 4.3
				08-Jan-03	2003	LE71880572003008SGS00	Appendix 4.3
Historical LULC data	Digital LULC polygon map	River State Ministry of Land and Housing	No	1995	1995	(Riv-MoLH, 1995)	Figure 4.3
Future LULC map	Document	GPHDA	No	2010	GPHDA	(GPHDA, 2010)	Figure 3.20 - 3.23
Elevation data	STRM digital elevation model map	STRM	Yes	Feb-00	NA	(USGS, 2004a, b)	Figure 4.4
Soil data	Digital Soil Map of the World (DSMW)	FAO	Yes	28-Feb-2007	NA	(FAO, 2007)	Appendix 4.2

Data	Type of data	Source	Published?	Date acquired/prepared	Year/Period covered	Entity ID/Reference	Location in thesis
Historical Rainfall data	Daily Rainfall Data	NIMET	No		1986-2013		To much to be included
Future Rainfall data	Statistically downscaled projections	Climate model projections based on IPCC's SRES emissions scenarios, A2 and A1B	Yes		Up to 2100	(McSweeney *et al.*, 2010)	Appendix 4.4
Flood mapping validation data	Annual maximum discharge (Q_P) data		Yes		1986 - 1998	(Okoro and Uzoukwu, 2013)	Table 6.1

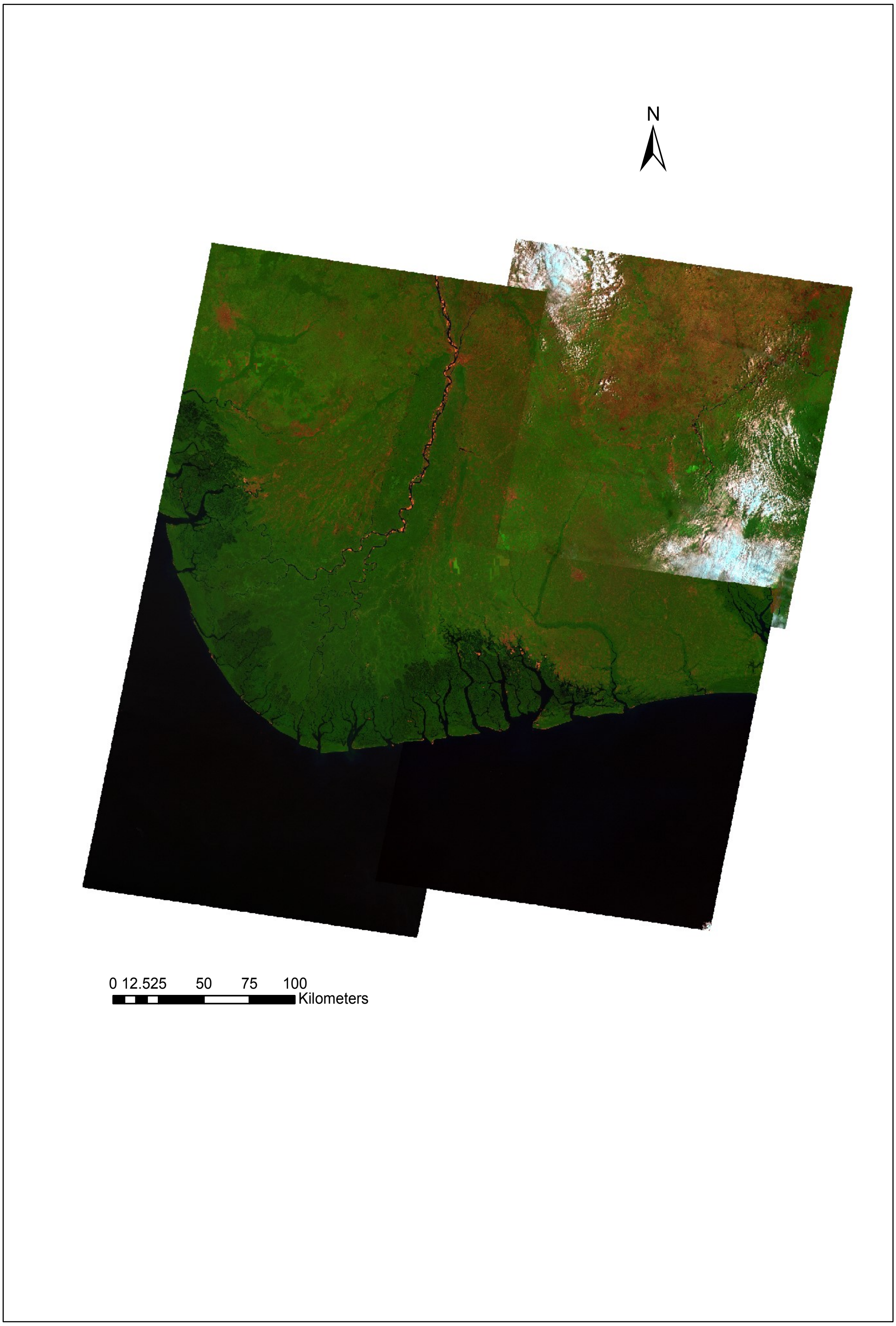


Figure 4.2 1986 land cover imagery used for LULC analysis. Source, United States Geological Survey

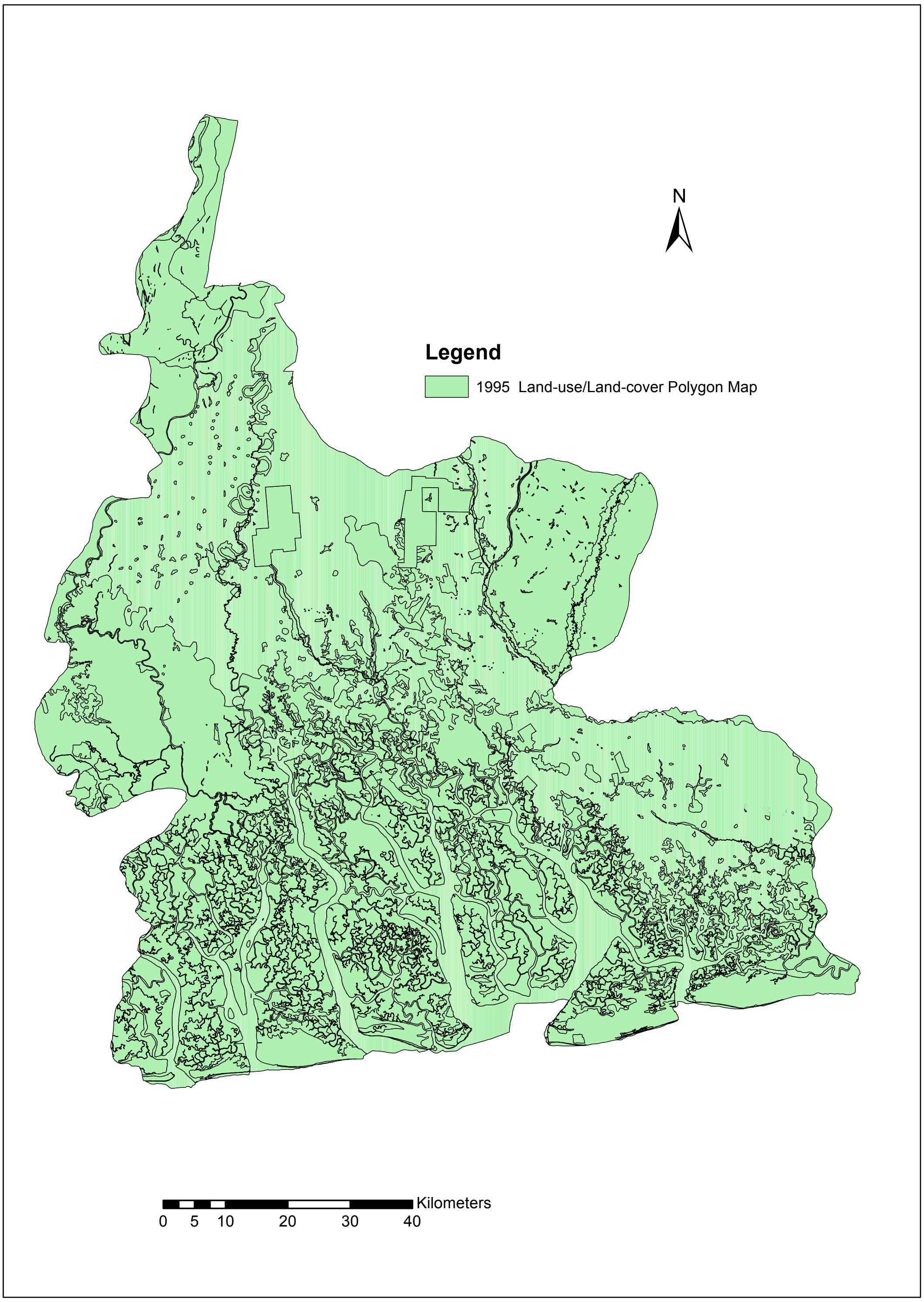


Figure 4.3 1995 Land use/Land-cover data (Polygon). Source: Rivers State Ministry of Land and Housing.

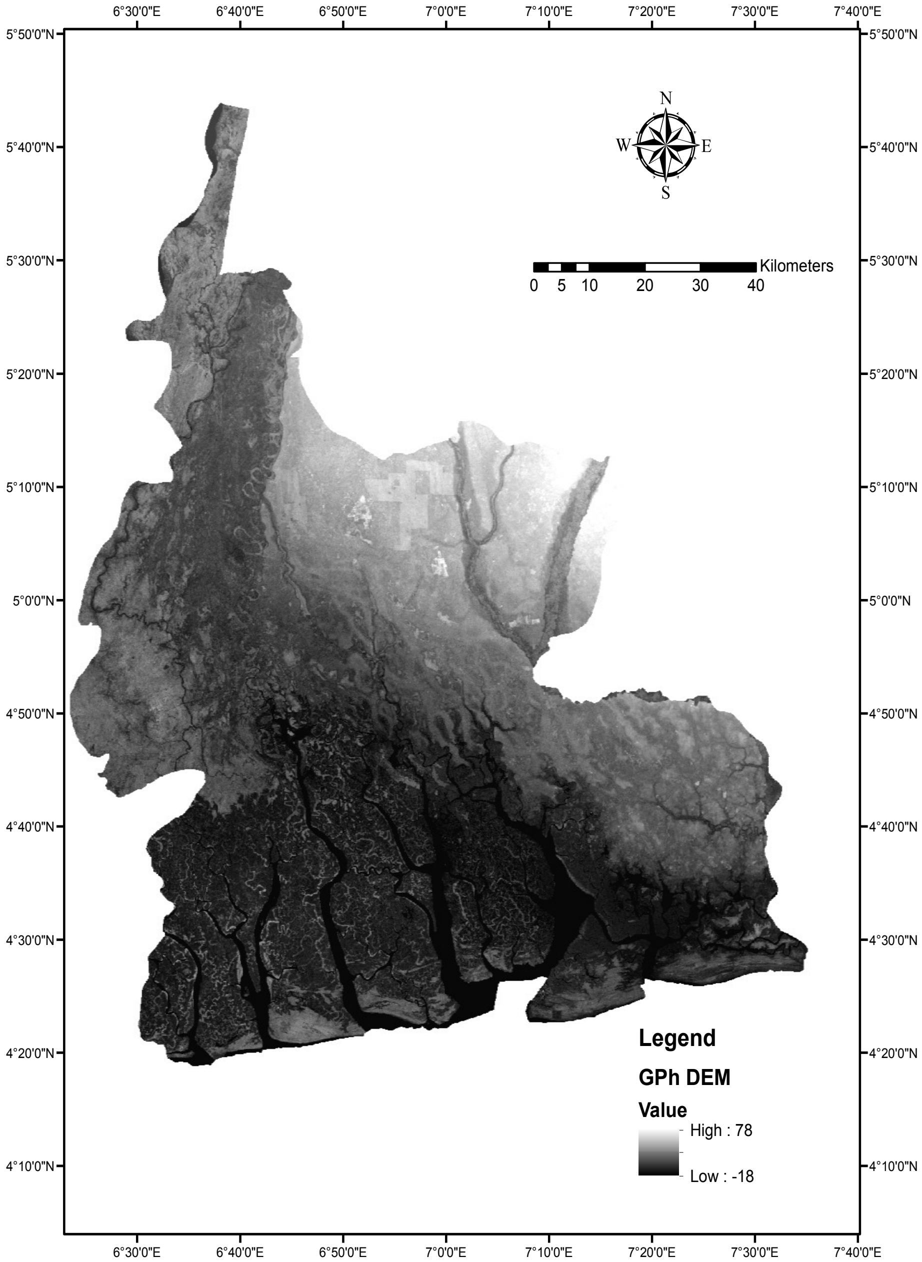


Figure 4.4 Clipped DEM data covering the entire study area. Source: Shuttle Radar Topography Mission (SRTM). Units of elevation are in meters and datum is the mean sea level.

4.4.1 Limitations of Study: Data quality

A number of data quality issues were identified with the data used as input in this study. Data are of high in quality if they are fit for purpose for analysis, decision making and planning (Verburg *et al.*, 2011). Usually data selected without explicit consideration of its suitability in terms of its quality and bias originating from data inventory & aggregation can increase uncertainty and affect results of an analysis (Lunetta *et al.*, 2006; Verburg *et al.*, 2011). Although overcoming known data quality problems was partly the motivation for this study, nevertheless, the main issues have to be clearly stated. Data quality issues in this study can be divided into three. Issues with the: A) Land use/Land cover data, B) Digital elevation data, and C) Flood modelling data.

A. **Land use/Land cover data.** Land use and land cover data play a crucial role in land-use change, climate change and impact assessments. They are often used to: generate landscape-based metrics, monitor status, assess landscape conditions and trends over a specified time interval (Lu *et al.*, 2004; Lunetta *et al.*, 2006; Yang *et al.*, 2015). Timely and accurate change detection of Earth's surface features is extremely important for improved understanding of natural phenomena. While, the accuracy of hydrologic modelling partly depends on the accuracy of the LULC input data (DeVantier and Feldman, 1993). the accuracy of LULC change detection results also depend on many factors, including: availability of accurate truth data, change detection method, familiarity and knowledge of the study area (Lu *et al.*, 2004; Lunetta *et al.*, 2006; Verburg *et al.*, 2011; Hegazy and Kaloop, 2015).

   The first issue with the LULC data quality in this study is that there was no good truth map suitable for validating changes between 1986, 1995 and 2003 maps. Google map is sometimes used for such analysis, but could not be applied in this study because it was composed of multi-date map tiles which could generate additional uncertainty in the accuracy assessment result. Moreover, the 1995 data is an independent LULC data and could be used to validate Landsat data around 1995. Again, this was not suitable for validating the 1986 and 2003 changes due to large temporal difference. However, to improve the accuracy of the change detection results in this study, the post-classification method deemed more reliable was applied. In addition, the author is familiar and has good knowledge of the study area.

The second issue with the LULC data that could increase uncertainty include observed over estimation in parts of the 1995 LULC map. Compared to the 1986 and 2003 Landsat data, parts of the 1995 data seem to be over-estimated. The third issue relates to presence of cloud cover in parts of the historical Landsat maps. Parts of the 2003 data had cloud cover. This data was acceptable because the affected part was insignificant and was not in the main area of interest (AOI). Generally, the cloud cover area in the River State map area was under 5% of the entire map area.

The fourth issue with quality of data used as input for analysing future LULC urban and flood changes was due to combination of multi data and multi-source data. That is, error may be introduced due to temporal inconsistency and combination of data from different sources. According to Verburg *et al.* (2011), monitoring and analysing changes in LULC require consistent data over a longer period of time. Preferably, such data should be derived from exactly the same data source that applies the same processing techniques. Again, the issue of scale of accuracy arises when these LULC data are combined, so there is a disincentive to combine them (DeVantier and Feldman, 1993). Apart from the issue of data combination, by digitising the 2060 Masterplan layout plan there could be additional uncertainty due to digitisation error.

B. **Topographic or Digital elevation data (DEM).** Topographic data is a crucial data input for hydrological modelling. The main way of characterising topography is by the use of satellite-based DEM which requires high-accuracy as well as high-resolution elevation data (Satgé *et al.*, 2013; Yan *et al.*, 2013). However, this kind of data is expensive and not often not available in developing countries such as Nigeria. Especially in Africa (the region of this study), quality of such data remains poor in the (Satgé *et al.*, 2013). In this study, the 3 arc or 90 x 90m DEM freely available DEM for Africa was used. It is considered coarse when compared to the 1arc or 30 x 30m DEM available for North America (Kreiselmeier, 2015). The issue is that coarse data result in additional uncertainties due to vertical and horizontal misrepresentation in the model (Kreiselmeier, 2015). The use of such data may induce modelling errors that may or not be compensated by model parameters tuning. In such regions, the validation of model result is an important step in the modelling procedure.

Apart from the resolution, the near-global STRM data dataset is affected by random noise and radar speckles. Consequently, in terms of absolute height error, the accuracy of SRTM topographic data ranges between 5.6 and 9.0 m at 90% confidence level (Rodriguez *et al.*, 2006; Mukolwe *et al.*, 2016). However, this study area has a low relief terrain. Hence, the 90 x 90m STRM data was acceptable because prior studies have revealed that large vertical errors in SRTM data is high in areas with high-relief terrain, but is smaller areas with low- to medium-relief (Falorni *et al.*, 2005; Patro *et al.*, 2009; Wang *et al.*, 2012). Therefore, this dataset could be suitable for modelling flood in low-relief areas, such as floodplains, rivers (lower and mid-reaches) and deltas such as the GPH watershed.

C. **Hydrodynamic calibration and validation data:** The input data requirement for hydrodynamic modelling also consist of inflow flood hydrograph data. However, in developing countries such as Nigeria, India, Bangladesh etc., there is a serious problem of data availability in such countries which limits the potential for calibrating hydrodynamic models (Patro *et al.*, 2009; Eludoyin *et al.*, 2011; Mmom and Fred-Nwagwu, 2013). In the context of hydrodynamic modelling, calibration involves a process of varying the parameter values to obtain an optimum level of fit between model predictions and observations. Validation refers to evaluating the performance of the model in predicting the observations (Patro *et al.*, 2009). Calibration can be done through optimization of model performances. Data required for calibration and validation are time-varying discharge and water levels at the gauging sites of rivers, which was unavailable for the study area. Studies have shown that the lack of sufficient or accurate calibration and validation data sets in addition to errors due to topographic misrepresentation could result in large uncertainties in the final model results (Garg *et al.*, 2003; Pappenberger *et al.*, 2005; Patro *et al.*, 2009).

Despite the lack of observed flow data for full hydrologic characterisation of the basin under study. As seen in several studies, methods that reliably predict streamflow in ungauged basins exist and include regionalisation of hydrologic parameters, index-gauge methods, and macro-scale hydrological models (Ford *et al.*, 2002; Patro *et al.*, 2009; Sorrell, 2010; Minihane, 2012). Regionalisation method was used in this study where flow characteristics for the ungauged basin was estimated based on physical basin characteristics such as area, roughness coefficient, channel slope, channel bottom width, reach length, etc. This method was deemed reliable because experience from existing studies show parameter estimation based on physical basin characteristics provide reasonable estimates of model parameters (Lange and Leibundgut, 1999; Ford et al., 2002; Patro et al., 2009; Sorrell, 2010; Minihane, 2012).

4.5 RESEARCH METHODS AND PROCEDURE.

In order to address the research questions in this study, post-classification method approach was used to detect changes to land-use/land-cover (LULC), Hydrologic modelling was used to estimate the effects of the LULC changes and rainfall on hydrology. One dimensional steady state hydraulic modelling approach was used to estimate the effects on flood hazard parameters, while flood mapping approach was used to visualise the changes in the flood hazard. Figure 4.5 presents the general procedure of the study. Again, the main methods involved are LULC change detection analysis, hydrological modelling, hydraulic modelling and mapping.

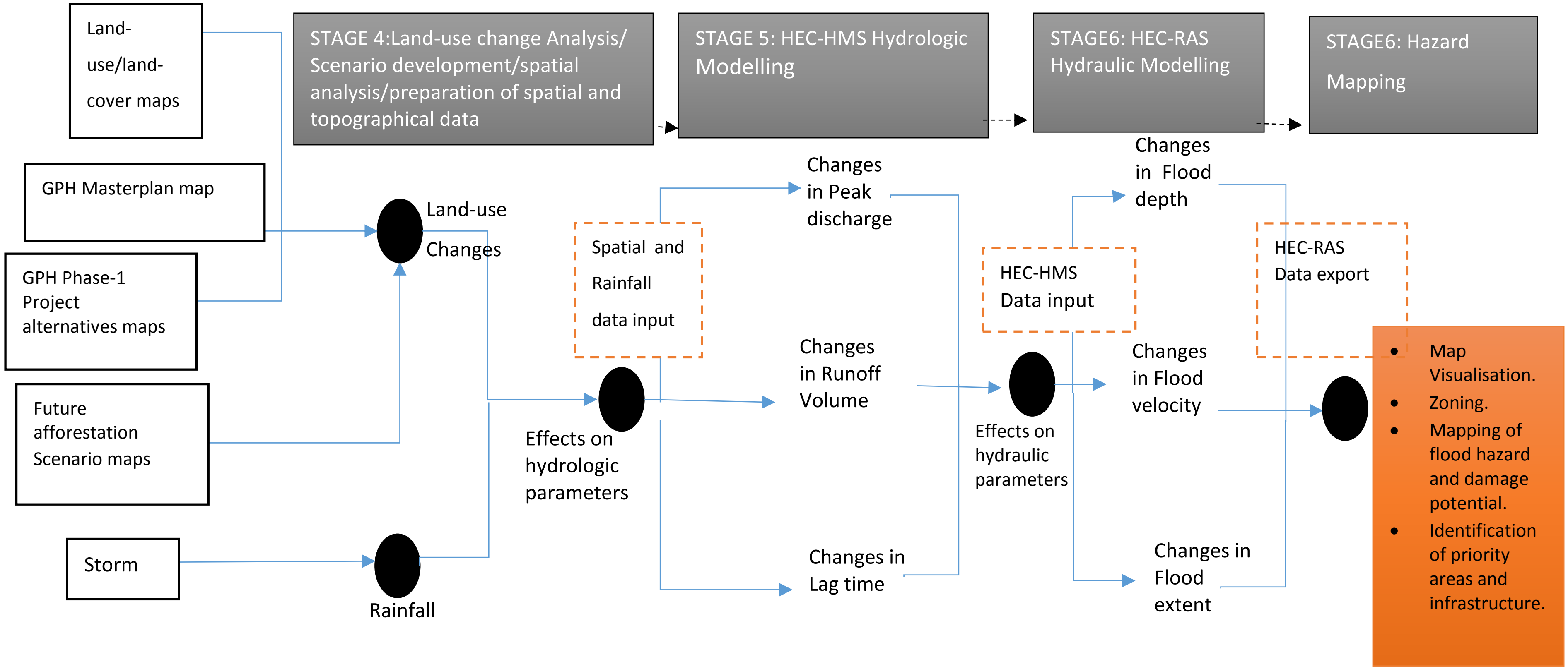


Figure 4.5 The general work flow of this study. Main methods are LULC change detection analysis, hydrological modelling, hydraulic modelling and mapping.

4.6 LAND-USE/LAND-COVER CHANGE DETECTION ANALYSIS.

Change detection is the process of identifying changes in the state of an object or phenomenon by observing it at different times (Singh, 1989). With respect to land-cover changes, it involves detection of the differences in the nature and extent of the land-cover from remotely sensed multi-temporal dataset (Singh, 1989; Afify, 2011). According to Afify (2011), it embroils the application of remotely sensed multi-temporal dataset to quantitatively analyse the changes in land-cover classes. This approach was also valuable for providing input for modelling the impact of LULC change on the hydrology of the GPH watershed. The reason for adopting this approach was because it provides valuable information for understanding change mechanism. Moreover, it provides crucial information on the magnitude and trend LULC changes in a particular area (Singh, 1989; Yang *et al.*, 2015). Furthermore, remotely sensed satellite data provides the means of estimating land-cover changes in an accurate, effective, and consistent way (Singh, 1989; Yang *et al.*, 2015).

Change detection has been applied in a number of ways to understand the extent of Land-cover changes (Dewan and Yamaguchi, 2009; Afify, 2011), hydrological footprints of urbanisation (Oni *et al.*, 2015), urbanisation (Deng *et al.*, 2009), urban sprawl (Zanganeh *et al.*, 2011). Change detection has also been used for: the assessment of the effects of the deforestation (Peiman, 2011), the study of shifting cultivation; the study of changes in vegetation phenology. It has also been applied in: damage assessment; crop stress detection; disaster monitoring; snow-melt measurements, daylight analysis of thermal characteristics etc. (Singh, 1989). In this study, change analysis was specifically applied to estimate the extent and nature of LULC changes in the GPH watershed.

4.6.1 Change Detection Methods and Techniques.

Assessing and monitoring changes to the earth's surface by classifying and mapping LULC is an essential requirement for global environmental change research (Shalaby and Tateishi, 2007; Xie *et al.*, 2008; Iqbal and Khan, 2014). The traditional means of monitoring change with remote sensing data have relied on photography and other field data. While these methods are appropriate for investigating changes in a local area, they are however not suitable for investigating large scale and long changes term. Hence, the change detection approach is the widely preferred approach for investigating long term and large scale changes (Muriithi, 2016; Purwanto *et al.*, 2016).

Several change detection methods and techniques are available for mapping land-cover changes using digital remotely sensed data (Singh, 1989; Lunetta *et al.*, 2006; Deng *et al.*, 2009; Moradkhani *et al.*, 2010; Afify, 2011; Peiman, 2011; Hegazy and Kaloop, 2015). They include direct multi-date classification, image differencing, ratioing, vegetation index differencing, principal component analysis (PCA), post classification comparison, image regression, image ratioing, vegetation index differencing, background subtraction, change vector analysis and change object methods (Singh, 1989; Afify, 2011; Yang *et al.*, 2015). Two basic categories are distinguished in studies. They include pre-classification and post-classification methods. These approaches are differentiated based on their data transformation procedures and techniques involved in delineating areas of significant change (Singh, 1989).

Pre-classification.

Pre-classification techniques also known as binary change detection techniques determine differences between two images prior to any classification process (Lu *et al.*, 2005; Al-doski *et al.*, 2013). It include a variety of techniques that make direct use of multi-temporal satellite imagery to generate change or no change maps (Al-doski *et al.*, 2013). This approach often allows the setting of threshold for the magnitude of change to be detected. As shown in Table 4.2, many binary or pre-classification techniques have been compared and applied to assess and identify LULC changes such as: Image Differencing (ID) (Wu and Tsai, 2000), Band Image Differencing (Chavez and MacKinnon, 1994), Image rationing (Lu *et al.*, 2005), Spectral Change Vector Analysis (Chen *et al.*, 2003), Principal Component Analysis (Byrne *et al.*, 1980), Combination of ID and PCA (Lu *et al.*, 2005), Vegetative Index Differencing (Lyon *et al.*, 1998; Mas, 1999) and others.

The basic premise in pre-classification techniques is measuring the nature of changes, which means changes in the features of interest that will result in changes in radiance or reflectance values (Lu *et al.*, 2005). Generally, pre-classification techniques are considered more accurate change detection techniques because, they are uncomplicated, effective for identifying and detecting change. However, they are not suitable for the objective of this study because although they are not premised on measuring extent of change, they cannot provide details of the nature of change or matrix of change information (Lu *et al.*, 2005). Moreover, other issues include: selection of thresholds or vegetative index. It is also over sensitive to mis-registration of pixels (Singh, 1989; Lu *et al.*, 2005; Al-doski *et al.*, 2013).

Post-classification change detection.

Post-classification change detection defines change by comparative analysis of independently produced classifications for different dates (Singh, 1989). This approach typically reports changes in form of 'from to changes' between classes or total area between two dates. It means this technique can provide details of the nature of change or matrix of change information. The post-classification comparison method has proven to be the most popular approach in change detection analysis (Hodges *et al.*, 1984; Singh, 1989; Lu *et al.*, 2005; Muzein, 2006; Deng *et al.*, 2009; Abd El-Kawy *et al.*, 2011; Peiman, 2011; Al-doski *et al.*, 2013; Hegazy and Kaloop, 2015). As shown in Figure 4.6, the approach begins with pre-processing stage that involves the rectification of more than one classified image; followed by a classification stage that involved independent classification of respective images and then thematic maps are generated. The last is the post-processing stage which includes change detection, i.e. comparison of the corresponding classes or themes to identify areas where change has occurred.

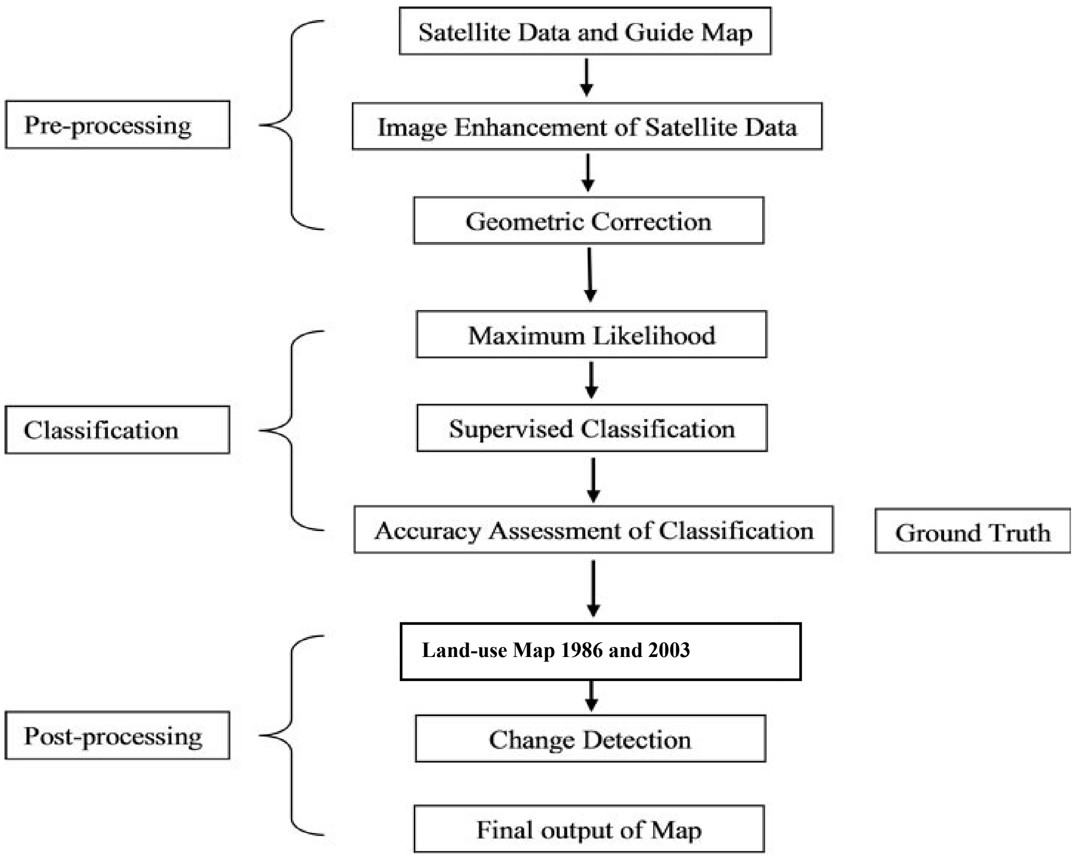


Figure 4.6 Flow chart of Land-use classification procedure, adapted from Singh and Kumar (2012).

Table 4.2 Change Detection Methods (Source: Singh, 1989; Lu et al., 2004, 2005; Afify, 2011; Al-doski et al., 2013).

Technique	Characteristics	Pros and Cons
Image Differencing (ID)	Image differencing change detection is performed by subtracting the digital number (DN) value of a pixel for a given band from the DN value of the same pixel for the same band of another date. The pixels of changed areas are expected to be distributed in the two tails of the histogram of the resultant image, and the unchanged area is grouped around zero. This is a simple method that easily interprets the resultant image. However, it is crucial to properly define the thresholds for detecting change from non-change areas.	Image differencing is the most widely used binary technique for change detection used in a variety of geographical environments Singh (1989), however Riordan (1980) pointed out the difficulty in applying mainly its high sensitivity to misregistration and the existence of mixed pixels. Weismiller et al. (1977) established that the method may be too simple to deal adequately with all factors involved in detecting changes in a natural scene as too much information may be discarded during the subtraction process.
Band Image Differencing BID	In this method, different image bands have their own reflectance characteristics for each land-cover type. The image differencing results between images bands of two dates have varying capabilities in identifying land cover changes. First, the image differencing was done for each band, i.e. ID (TMi) = TMi (t1)–TMi (t2). Thresholds are then determined to identify the land cover change and to provide a binary image for each band. That is, 1 as change and 0 as non-change. Then, the binary images were developed to provide a new image. If the value of a pixel is greater than or equal to 4 for a TM image (with six bands), then the pixel belongs to change class; otherwise, it belongs to unchanged class based on the majority rule	This method does not provide a detailed change matrix. It requires selection of thresholds
Image ratioing IR	Ratioing is considered a rapid means of identifying areas of change. It involves calculation of the ratio of two registered images from different dates, on a band-by-band basis. In the changed areas, the ratio values will be significantly greater than 1 or less than 1 depending on the nature of the changes between two dates of the images.	Ratioing is also a simple and rapid means to identify changed areas. However, its result has been criticized because it is based on non-normal distribution (Lu *et al.*, 2005).
Spectral Change Vector Analysis (CVA)	CVA generates two outputs: a change vector image and a magnitude image. The spectral change vector explains the direction and magnitude of change from the first to the second date. The total change extent per pixel is calculated by determining the Euclidean distance between end points through n-dimensional change space of the CVA.	An advantage of CVA is its ability to process any number of spectral bands desired and to produce detailed change detection information. However, this method is considered computationally very demanding as the data have to be geometrically corrected. Moreover, the performance of the procedure is sensitive to its parameter setting (Singh, 1989).

Technique	Characteristics	Pros and Cons
Combination of ID and PCA (IDPCA)	This technique is similar to the multi-temporal PCA. The only difference between them is the change of single image to resultant image from image differencing. It is necessary to examine thoroughly the components and multi-date composite image to determine which component can give the best change information	The difficulty is to determine which component image indicate the main land cover changes.
Vegetative Index Differencing (VID)	This method generates vegetation index separately after subtracting the second-date vegetation index from the first-date vegetation index difference that was used for land-cover change detection.	It enhances the differences in the spectral response of various features and minimises the impacts of topographic effect. At the same time, it enhances random noise or coherence noise
Post-classification comparison	Classifies multi-temporal images separately into thematic maps, and subsequently implements comparison of the classified images on pixel by pixel basis	This technique reduces the effects of atmospheric, sensor and environmental differences between multi-date images. It is capable of generating change matrix information. However, it demands a huge amount of time to create classify maps. Importantly, the final accuracy depends on the quality of the classified image of each date

Rationale for Adopting Post-Classification Method.

The post-classification comparison approach was adopted for this study. This method was adopted because it is capable of addressing the research question relating to LULC changes. It is capable of addressing questions on the extent and the nature of change or matrix of change information such as “from to” and to and total area of change caused by urbanisation (Al-doski *et al.*, 2013; Mmom and Fred-Nwagwu, 2013; Enaruvbe and Ige-Olumide, 2014). Secondly, it bypasses the problem of getting accurate registration of multi-date images (Singh, 1989) Thirdly, it minimises sensor, atmospheric and environmental differences because of the independent classification of data, by that reducing the problem of normalising for atmospheric and sensor differences between two dates (Al-doski *et al.*, 2013). Table 4.2 shows a comparison between the different methods.

In addition, this method was also adopted because it is reliable and has long been applied in several studies for detecting urban LULC changes. For example, it was successfully applied for: (1) Studying urban growth in the city of Yazd, Iran (Zanganeh *et al.*, 2011). (2) Mapping and monitoring changes in LULC in the Twin Cities of Minnesota metropolitan Area (Yuan *et al.*, 2005). (3) Mapping LULC changes and erosion risk at Azad Jammu and Kashmir, Pakistan (Iqbal and Khan, 2014). (4) Identifying the long-term trend of LULC changes and its causes in the western Nile Delta of Egypt (Abd El-Kawy *et al.*, 2011). (5) Mapping and monitoring LULC changes in the North-western coastal zone of Egypt (Shalaby and Tateishi, 2007). (6) Understanding the LULC changes in New Burg El-Arab City in Egypt (Afify, 2011).

4.6.2 Post Classification Procedure.

The change detection procedure followed in this study can be summarised under five (5) main steps (Figure 4.7), including: (1) Data acquisition, (2) Pre-processing, (3) Supervised classification (4) Change detection analysis was used for deriving results. For emphasis, the goal was to analyse the historical urban growth pattern and extent; but ultimately to provide data input for hydrologic and hydraulic modelling.

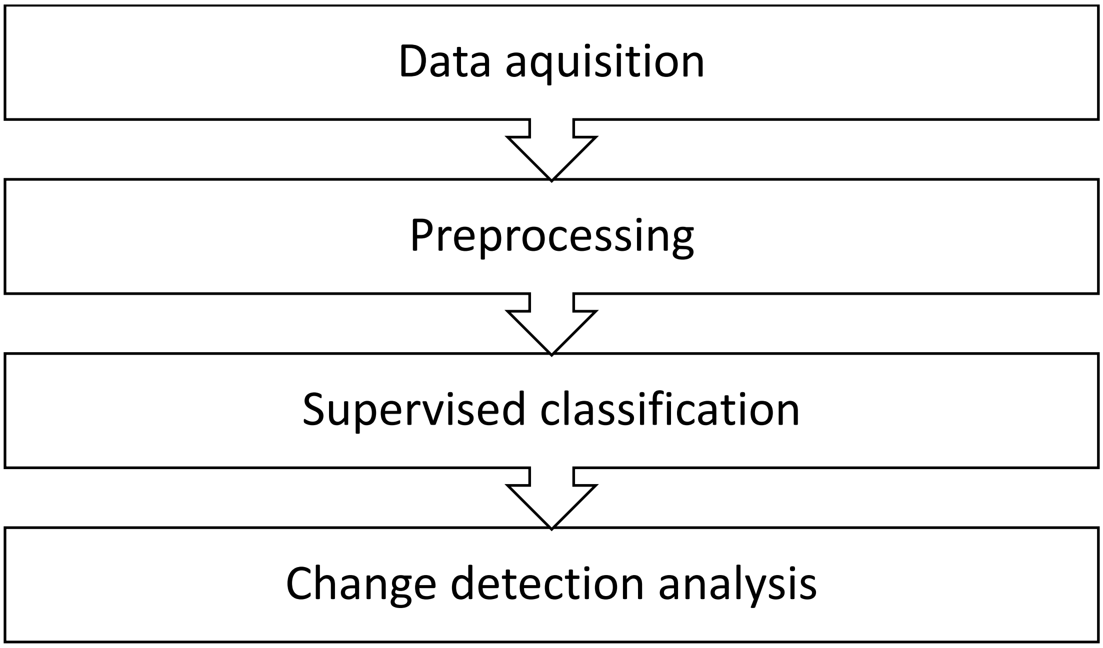


Figure 4.7 Post classification change detection procedure followed in this study including Data acquisition, (2) Pre-processing, (3) Supervised classification (4) Change detection analysis.

4.6.3 Data acquisition.

In this study, multi-temporal and multi-spectral data set were obtained to generate digital maps for the LULC change detection analysis. The historical data set acquired include: 1xThematic Mapper (TM) images for the year 1986 (Figure 4.8); 1x Enhanced Thematic Mapper plus (ETM+) map for the year 2003 (Appendix 4.3); and 1 x polygon LULC map for the year 1995 (Figure 4.3.). These dates were chosen to benchmark approximate decadal changes. Year 2003 map was considered baseline map because of the unavailability of suitable maps around year 2009 when the GPH development commenced. These multi-sourced dataset vary in their spatial and spectral resolutions (which is often the case) and have been successfully used to study changes spanning over decades (Abd El-Kawy *et al.*, 2011; Zanganeh Shahraki *et al.*, 2011; Du *et al.*, 2012).

The 30m resolution ETM+ and TM imageries were of moderate resolution (Table 4.3). These imageries were obtained from the USGS Earth Explorer site (http://earthexplorer.usgs.gov/), whereas, the 1995 LULC polygon map was obtained from the Rivers State's Ministry of Land and Housing (Riv-MoLH, 1995). The main reason for using TM and ETM+ sensor data was first due to availability. Second, they provided data that cover the spatial extent of the entire study area. Although a higher resolution map i.e. the light detection and ranging (LiDAR) data can provide a more accurate estimate (Tsui *et al.*, 2012; Parent *et al.*, 2015). However, this type of data was not readily available for the study area. Generally, observations over large areas or regions for generating LiDAR data remain uncommon and is associated with high cost (Tsui *et al.*, 2012). Lastly, the rationale for sourcing the vector map from the Ministry of Housing was due to the difficulty in obtaining a cloud free map for the 1995 time period.

Table 4.3 Main features of the satellite images used for LULC change detection analysis.

Year	Path/row	Sensor	Satellite	Original bands numbers	Pixel resolution	Spectral range	Map Band combination
1986	188/056 188/057 189/056 189/057	TM	Landsat-5	1,2,3,4,5,7	30m	0.450 - 2.35 µm	1. Red 2. Green 3. Blue
2003	188/056 188/057 189/056 189/057	ETM+	Landsat-7	1,2,3,4,5,7	30m	0.450 - 2.35 µm	1. Red 2. Green 3. Blue

Moreover, data acquisition for recent maps (2007 onwards) was hindered due to high cloud cover and satellite scanner issues. 2009 was initially selected as the baseline year because of the commencement of the GPH development. Due to high cloud cover and sensor scanner issues, 2003 was chosen as the baseline year because of availability cloud-free scenes for this year. All maps (scale 1: 1,100,000) used had cloud cover under 20% see Figure 4.8 and 4.9.

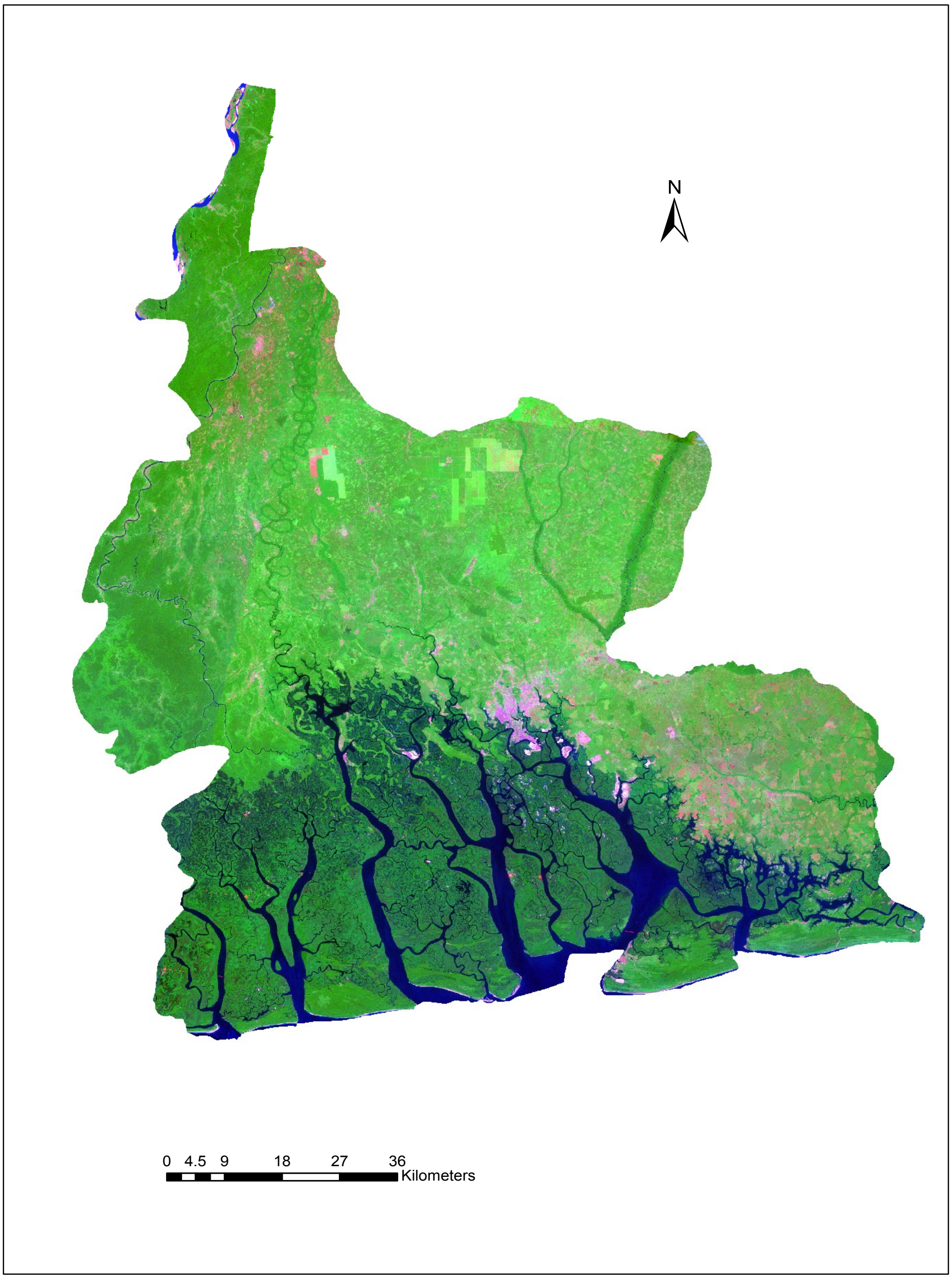


Figure 4.8 Map showing 1986 Unclassified Landsat TM image clipped to the boundary of River state (Sourc: USGS)

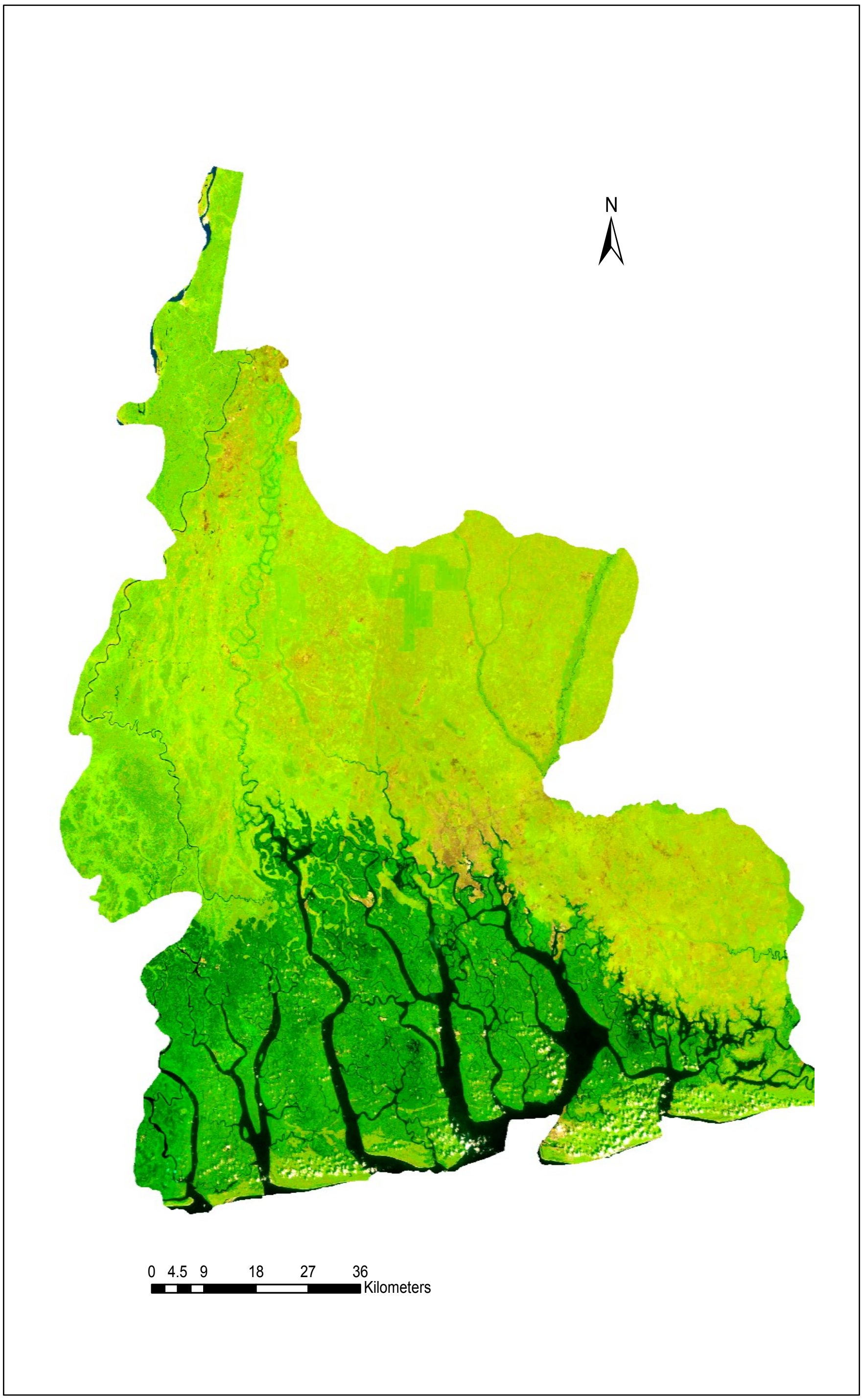


Figure 4.9 Map showing 2003 Unclassified Landsat TM image clipped to the boundary of River state. (Source: USGS)

4.6.4 Pre-processing (Image processing).

Image Correction.

Next, image restoration was carried out in ArcMap 10.1, prior to change detection analysis. At this stage the digital images were manipulated to relate the data to the true biophysical environment. A series of image correction techniques were used such as: mosaicking, clipping, geometrical correction, map registration, atmospheric correction. Due to the position and scale of the map, four tiles were obtained and merged for each year. For example, Figure 4.2, the 1986 map was clipped with a polygon map of the entire River State. The maps were then spatially referenced to WGS_84_UTM_Zone_32N in the Universal Traverse Mercator (UTM) system.

Image enhancement.

After mosaicking, geometrical correction, map registration, atmospheric correction, image enhancement was conducted. Image enhancement involved the adjustment of image values so as to highlight distinct feature and create classes from within the images and to improve visual interpretability on the map (Abd El-Kawy *et al.*, 2011). This was particularly useful for visual interpretation of the LULC classes in the image. While the range of image enhancement techniques are broad, composite colour generation technique was applied for enhancement because it makes the fullest use of the capabilities of the human eye (Horning, 2004). Table 4.4 and 4.5 respectively show available TM and ETM+ sensor bands downloaded for combination.

Table 4.4 Landsat 5 Thematic Mapper Sensor bands and Wavelengths of the 1986 Imagery. Source: USGS.

Landsat 5 (TM sensor)	Wavelength (micrometres)	Colour	Resolution (meters)	Landsat 5 (TM sensor)	Wavelength (micrometres)
Band 1	0.45 - 0.52	Blue	30	Band 1	0.45 - 0.53
Band 2	0.52 - 0.60	Green	30	Band 2	0.52 - 0.61
Band 3	0.63 - 0.69	Red	30	Band 3	0.63 - 0.70
Band 4	0.76 - 0.90	Reflected Infrared	30	Band 4	0.76 - 0.91
Band 5	1.55 - 1.75	Reflected Infrared	30	Band 5	1.55 - 1.76
Band 6	10.40 - 12.50	Thermal	120	Band 6	10.40 - 12.51
Band 7	2.08 - 2.35	Reflected Infrared	30	Band 7	2.08 - 2.36

Table 4.5 Landsat 7 ETM+ Sensor Bands and Wavelengths of the 2003 Imagery. Source: USGS.

Landsat 7 (ETM+ sensor)	Wavelength (micrometres)	Colour	Resolution (meters)	Landsat 7 (ETM+ sensor)	Wavelength (micrometres)
Band 1	0.45 - 0.515	Blue	30	Band 1	0.45 - 0.516
Band 2	0.525 - 0.605	Green	30	Band 2	0.525 - 0.606
Band 3	0.63 - 0.69	Red	30	Band 3	0.63 - 0.70
Band 4	0.75 - 0.90	Reflected Infrared	30	Band 4	0.75 - 0.91
Band 5	1.55 - 1.75	Reflected Infrared	30	Band 5	1.55 - 1.76
Band 6	10.40 - 12.5	Thermal	60	Band 6	10.40 - 12.6
Band 7	2.09 - 2.35	Reflected Infrared	30	Band 7	2.09 - 2.36
Band 8	.52 - .90	Panchromatic	15	Pan Band	.52 - .91

Using different spectral band combinations to display a scene enabled different features to be distinguished within the scene (Figure 4.10). In this study several spectral band combinations were carried as seen in Figure 4.10.

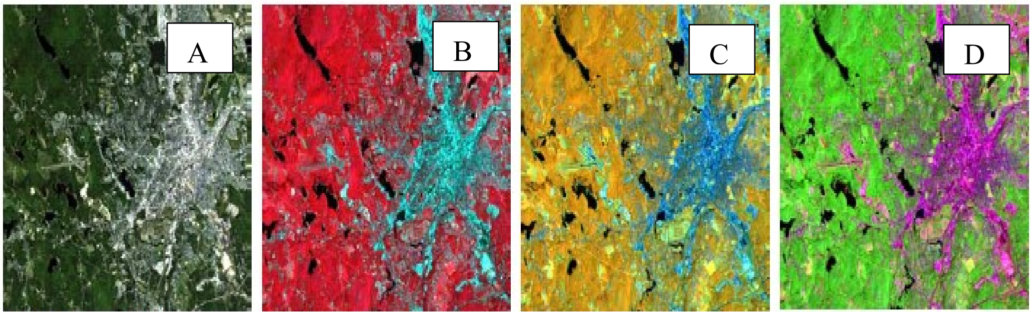


Figure 4.10 Composite band combinations considered during image enhancement (Parece *et al.*, nd) A (RGB=Bands 3, 2, 1), B (RGB=Bands 4, 3, 2), C (RGB=Bands 4, 5, 3), D (RGB=Bands 7, 4, 2).

Natural colour band combination (3, 2, 1) characterised by short wavelengths was applied for year 1986 and 2003 image classification. The combination of these visible bands was preferred because it makes ground features appear like colours to the human visual system and also because this combination is suitable for urban studies. However, in this study, 1986 and 2003 maps were remotely sensed from different sensors vary to a degree (see Figure 4.8 and 4.9), because each band most likely carry different information (Parece *et al*, nd). The disadvantage is that cleared and sparse vegetation is not as easily detected here as in the 4, 5, 1 or 4, 3, 2 combination. Moreover, vegetation types are not very distinct as in 4, 5, 1 combination. In this study, 1986 map showed grey and pink colours for urban areas, dark green for mangrove vegetation, mid green for forest areas, light green for Agricultural areas, orange for clouds, blue to black for river. Whereas 2003 map was some worth different, with brown and grey for urban areas, dark green for mangrove, mid green for forest, light green and yellow for agricultural land, white for cloud, and black for river.

Supervised classification.

The image classification process involved conversion of multi-band raster imagery into a single-band raster with categorical classes that relate to different LULC classes (Nagi, 2011). In this study supervised classification (a deterministic method) was used. Supervised classification involved the process of clustering pixels into classes based on training data defined by the user (Richards and Richards, 1999). The supervised classification method was preferred over unsupervised classification because the LULC classes were already known from an existing classified map of the area. Secondly, it provides the advantage of indicating not just the magnitude of change but also the nature of change that has taken place through pixel by pixel comparison (Kafi *et al.*, 2014) Supervised classification in this study was conducted following the steps in Figure 4.11.

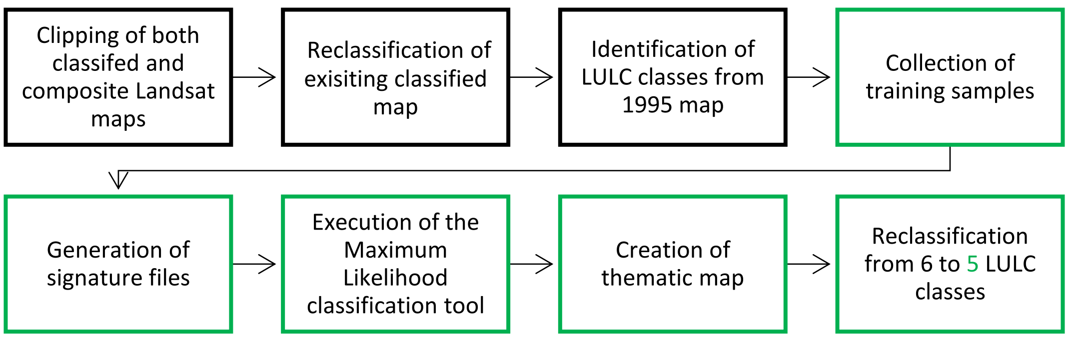


Figure 4.11 Supervised classification procedure in this study. Green boxes represents the main image classification steps in the process. Black boxes represent other steps in the process.

1. First, prior to the image classification process, all maps were clipped to the boundary of Rivers State. Clipped maps include (1) the existing 1995 classified map and (2) 1986 and 2003 composite maps.
2. Next, for classification purposes, the predefined 1995 was reclassified from the originally ten (10) classes to five (5) LULC classes as shown in Figure 4.12 and Table 4.6. Sand bar was excluded because it did not actually appear in the original map.

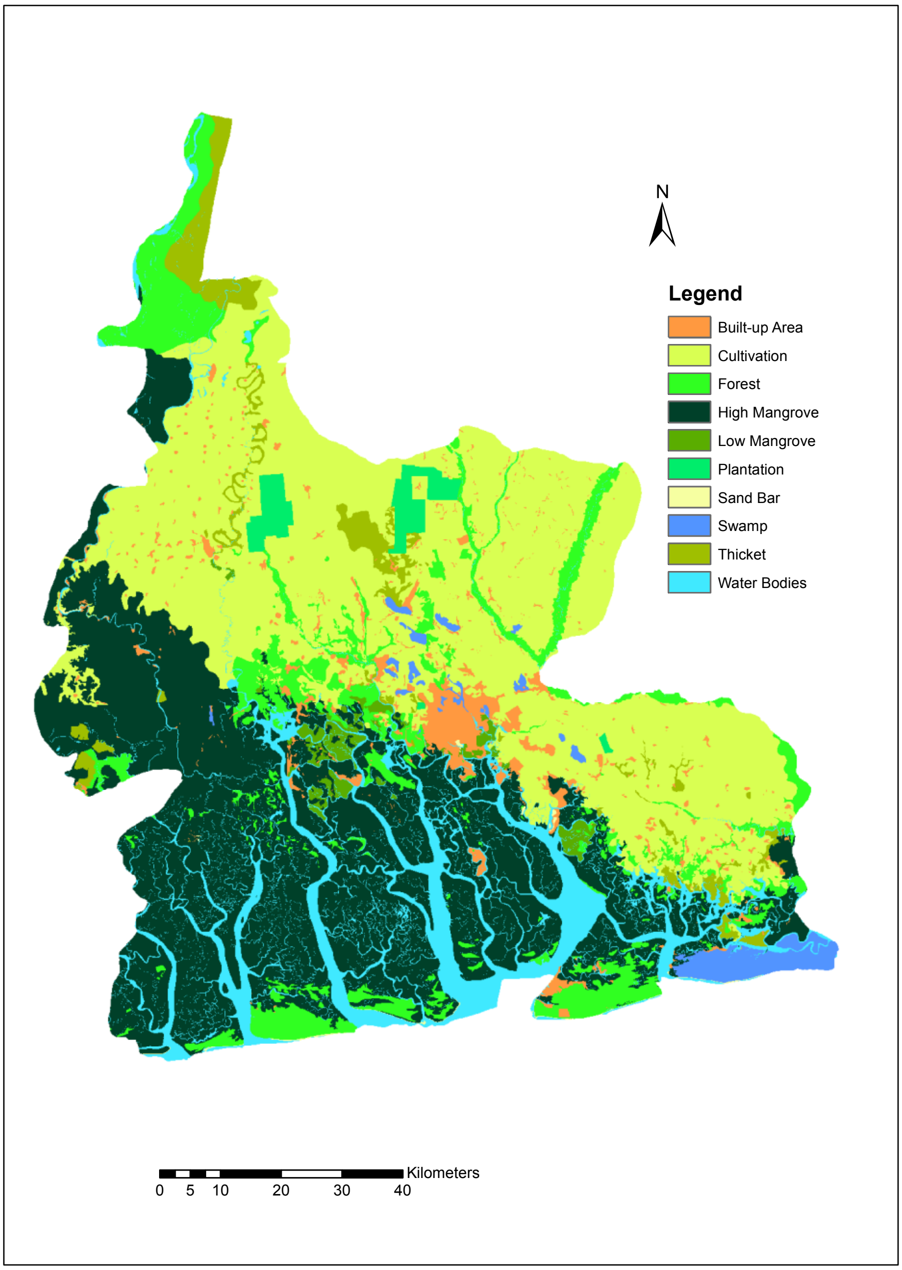


Figure 4.12 1995 Map of Rivers State used for re-classification. The map is made up of 9 LULC classes. (Source, Rivers State Ministry of Land and Housing).

Table 4.6 Table showing the re-classification of the 1995 Map from Ten to Five classes.

S/N	From	To
1.	Built-up area	Urban
2.	Forest	Forest
3.	Thicket	
4.	Swamp forest	
5.	Plantation	Agricultural land
6.	Cultivation	
7.	High Mangrove	Mangrove
8.	Low Mangrove	
9.	Water body	River
10.	Sand bar	Not included

3. Subsequently, known classes in 1995 were defined to identify pixels of unknown classes in 1986 and 2003 maps.
4. During classification, training classes were respectively collected from the 1986 and 2003 images (Lillesand *et al.*, 2014), for example see Figure 4.13. These were sample pixels representative of specific classes. These training classes were then used directly in ArcMap for classifying all pixels in the images.
5. Next, signature files were the generated and stored. A signature file stores spectral signatures of LULC across the series of bands (Nagi, 2011). Next, scatter plots were repeatedly used to ensure separability and good distribution of training samples to avoid "salt and pepper" effects (Nagi, 2011: 'no page'), See Figure 4.13.
6. Next Maximum Likelihood Classifier (MLC) tool was used for image classification. It assumes that a pixel has a certain probability belonging to a particular class and that probabilities are equal for all classes. Moreover, the input data in each band follow the normal distribution function (Muzein, 2006; Lillesand *et al.*, 2014). There are a variety of algorithms, but MLC is among the most commonly applied supervised classification techniques for classifying remote sensing image.

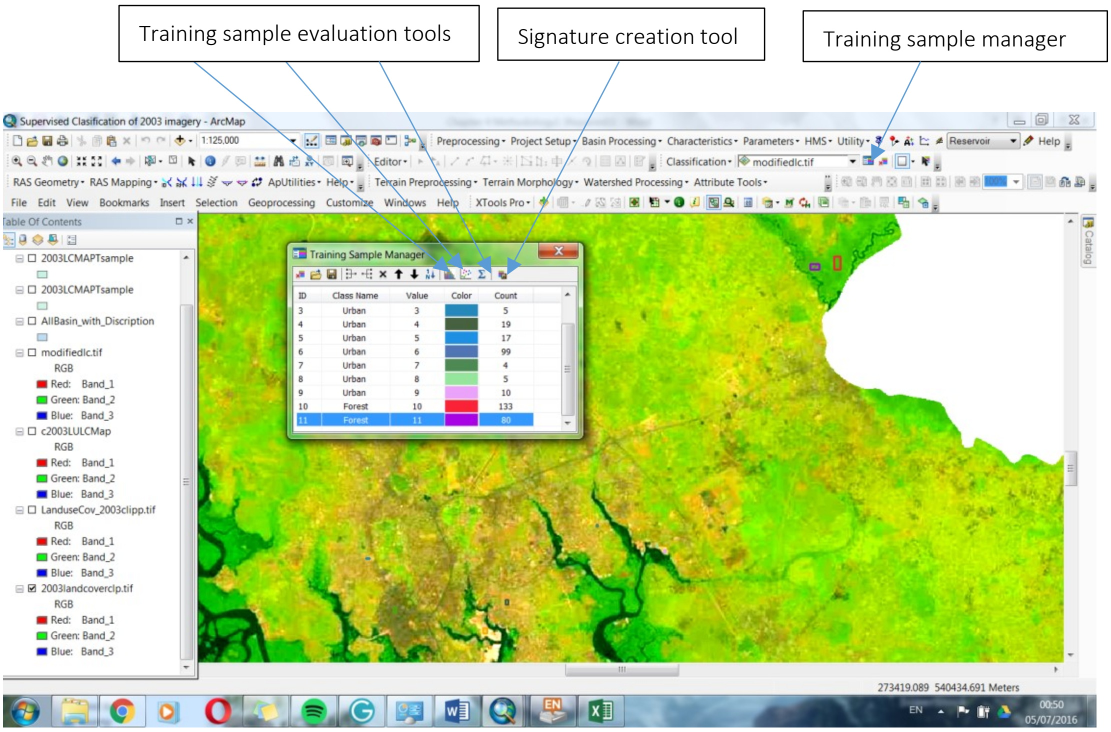


Figure 4.13 Showing 2003 imagery with training samples and signatures tools for supervised classification.

Unlike the minimum distance classification technique, MLC was selected because it uses a rigorous algorithm widely employed in studies. It was developed in a statistically acceptable manner based on probability theory and it is used when there is sufficient training data (Richards and Richards, 1999; Lillesand *et al.*, 2014). To execute this tool in ArcMap, the input image and the signature input signature file were respectively used for each scene.

7. Initially, the thematic maps were created with 6 classes including, Urban, Forest, and Agricultural land, Mangrove, River and Cloud.
8. Afterwards the LULC maps were then clipped to the actual frame of the watershed and later reclassified into five classes consisting of Urban, Forest, Agriculture, Mangrove and Water body. Note, for modelling purposes, River and Mangrove classes were categorised as waterbody because they fall into the same hydrologic soil group. Cloud class was excluded because it was not useful to the study and because its pixels were mainly located outside the watershed boundary.

Post Classification

Accuracy Assessment.

After classification, accuracy assessment was meant to be carried out based on overall accuracy and kappa statistic methods. The term accuracy is used to express the degree of 'correctness' of a map classification (Foody, 2010; Olofsson *et al.*, 2013). Overall accuracy is normally generated using error matrix based on statistical evaluation on each LULC map. It provides the basis on which to both describe classification accuracy and characterise errors (Foody, 2010). However, accuracy assessment in this study was not possible because there was no suitable truth map available to validate the classified maps.

Usually, the main steps in accuracy assessment involves: (1) Random sampling and extraction of reference (truth) and classified map data using the extract value to point tool in ArcMap. (2) Comparison of reference map to classified map using error matrix. Data is organised using frequency and pivot tools in ArcMap.

Predicted class

Truth Class

n_{AA}	n_{AB}	n_{AC}	n_{AD}	n_{A+}
n_{BA}	n_{BB}	n_{AC}	n_{BD}	n_{B+}
n_{CA}	n_{CB}	n_{AC}	n_{CD}	n_{C+}
n_{DA}	n_{BD}	n_{AC}	n_{DD}	n_{D+}
n_{+A}	n_{+B}	n_{+C}	n_{+D}	n

Overall Accuracy = $n \sum_{k=1}^{q} n_{kk} * 100$

Kappa Coefficient =

$$\frac{n \sum_{k=1}^{q} n_{kk} - n \sum_{k=1}^{q} n_{k+} n_{+k}}{n^2 - \sum_{k=1}^{q} n_{k+} n_{+k}}$$

k = number of codes, the row probabilities, and are the column probabilities.

Figure 4.14 The confusion matrix and kappa statistic classification accuracy that may be derived from it. The highlighted elements represent the main diagonal of the matrix that contains the cases where the class labels depicted in the image classification and ground data set agree, whereas the off-diagonal elements contain those cases where there is a disagreement in the labels (Foody, 2010).

In the error matrix, columns represented the truth classes extracted from the truth map, while the rows represent predicted classes from the classified maps (Figure 4.14). The overall accuracy is the total predicted pixels divided by the sum of the predicted pixels (of the major diagonal). According to Enaruvbe and Ige-Olumide (2014) overall accuracy of <50 is poor, 50-70% is moderate, while > 70% is considered good. Subsequently Kappa statistic is normally was used to measure of the magnitude of agreement between the reference and classified map

(Viera and Garrett, 2005). The interpretation of kappa statistics used can be found in Table 4.7, but mathematically, kappa is expressed as:

$$\text{Kappa (K)} = \frac{Observed\ Agreement - Expected\ Agreement}{1 - Expected\ Agreement}$$

Table 4.7 Interpretation of Kappa Values (Viera and Garrett, 2005).

Kappa	Agreement
< 0	Less than chance agreement
0.01–0.20	Slight agreement
0.21– 0.40	Fair agreement
0.41–0.60	Moderate agreement
0.61–0.80	Substantial agreement
0.81– 1.0	Almost perfect agreement

LULC change detection and analysis

After classification, the land use change detection was performed to estimate differences between two scenes.

This was done in two ways

(1) Magnitude of change
(2) Nature of Change.

(1) Magnitude of change - used to estimate degree of expansion or reduction in the LULC size resulting from the classification (Kafi *et al.*, 2014). Negative values meant reduction in LULC size whereas positive values indicated increase in the size LULC class.

Change detection (K) = $F - I$

It was also expressed as: percentage of change (A), expressed as $= \frac{F-I}{I} * 100$

K = Magnitude of change (i.e. degree of change)

A = Percentage of change (i.e. percentage increased or decreased)

F = First date (date of the first imagery analysed)

I = Reference date (date of the second imagery analysed)

(2) Nature of Change - used to describe the type of changes that have occurred between the two dates using a matrix table of "from – to" change class (Howarth and Wickware, 1981; Kafi *et al.*, 2014). The reason for this analysis was to interpret what the changes have been in a particular class from one year to the next. This study further describes the analysis of total gross gain, gross loss and persistence, absolute net change and swap changes in the landscape. In addition, the ratios of loss-to-persistence and gain-to-persistence were determined, for detailed description of the methods see Pontius *et al*. (2004).

4.7 MAPPING OF ALTERNATIVE LOCATIONS/ SCENARIO DEVELOPMENT.

The previous section dealt with steps taken to estimate historic LULC changes. This section deals with steps taken to estimate future LULC and rainfall changes. Importantly, it described which and how alternatives were mapped and how future scenarios were constructed. The goal was to prepare maps of location alternative obtained in the EIA, in addition to development of afforestation scenarios and presentation of storm scenarios.

4.7.1 Mapping of future LULC and Alternatives.

Alternatives initially considered for mapping in this study were based on the main alternatives considered in EIS report, including (1) the no-project alternative (2) delayed project alternative (3) location alternative (4) urban renewal of the old Port-Harcourt City and (5) the current project alternative (ERML, 2009). But finally location alternative of Phase-1 was mapped. The goal was to ultimately compare the relative effects of location alternative on peak discharge at subbasin scale. Hence, prior to mapping, some assumptions were made.

1. Due to data limitation, the LULC condition in year 2003 LULC map represents the baseline condition.
2. The 2060 urban LULC condition was determined assuming that the conditions of other LULC classes outside the GPH LULC map would largely stay the same.
3. Comparison of alternative locations was done for the entire Phase-1 project rather than Phase-1A project alone because of the small extent of the Phase-1A project area. This was based on the assumption that Phase-1B, 1C and 1D will be sited wherever Phase-1A was sited.

Procedure.

Mapping and estimation of future LULC changes involved six (6) main stages consisting of: selection of alternatives for mapping, digitisation of hard copy GPH maps, interpretation/reclassification of GPH LULC maps, overlay of digital maps on baseline map, and the estimation of future LULC changes.

1. **Selection of Alternatives**-Alternative locations selected for mapping and further analysis were located in three different areas namely:
    a. Bori
    b. Ogba/Omoku
    c. Port-Harcourt (the current Phase-1 project alternative). See location of alternatives in Figure 6.8.

    In terms of selection criteria, alternatives were selected for mapping if they had implications on land-use. The delayed alternative was not selected because it was based on time. Although the urban renewal alternative is likely to have some implication on land-use change, this alternative was not included because according to the EIS report urban renewal would involve the enhancement of the physical and social infrastructure of the urban areas. It would also involve construction and demolition of structures (ERML, 2009). In this study it was assumed that the spatial expansion and LULC changes due to urban renewal will not be significant given that demolition of the old structure is likely to cancel-out expansion from construction of new structures.

2. **Digitisation**- Digitisation is a process of converting the geographic features of an analogue map into digital format (Shaner and Wrightsell, 2000). The digitisation process was done, first by georeferencing the analogue maps (Masterplan and location alternative maps) to an appropriate projected coordinate system, i.e. WGS_84_UTM_zone_32N. Second, by creating an empty shape file. Third, by digitising the LULC classes. Note: the GPH Masterplan was digitised first followed by the digitisation of the location alternative.

3. **Interpretation/reclassification** of GPH LULC classes-As shown in Figure 4.15 all LULC classes from the GPH Masterplan were reclassified into 4 main classes i.e. Urban, Forest, Agriculture and Mangrove. As shown in Figure 4.15, urban related classes were reclassified to urban area class, the Golf course class was reclassified to agricultural land. Open space/riverine class was less explicit. However, with the aid of the truth map, the open space/riverine was reclassified to forest and mangrove classes

depending on the features identified in Google Earth map. Note: reclassification into the 4 distinct classes was done because of the hydrologic modelling. LULCs are often simplified into fewer classes for hydrologic modelling (Feldman, 2000).

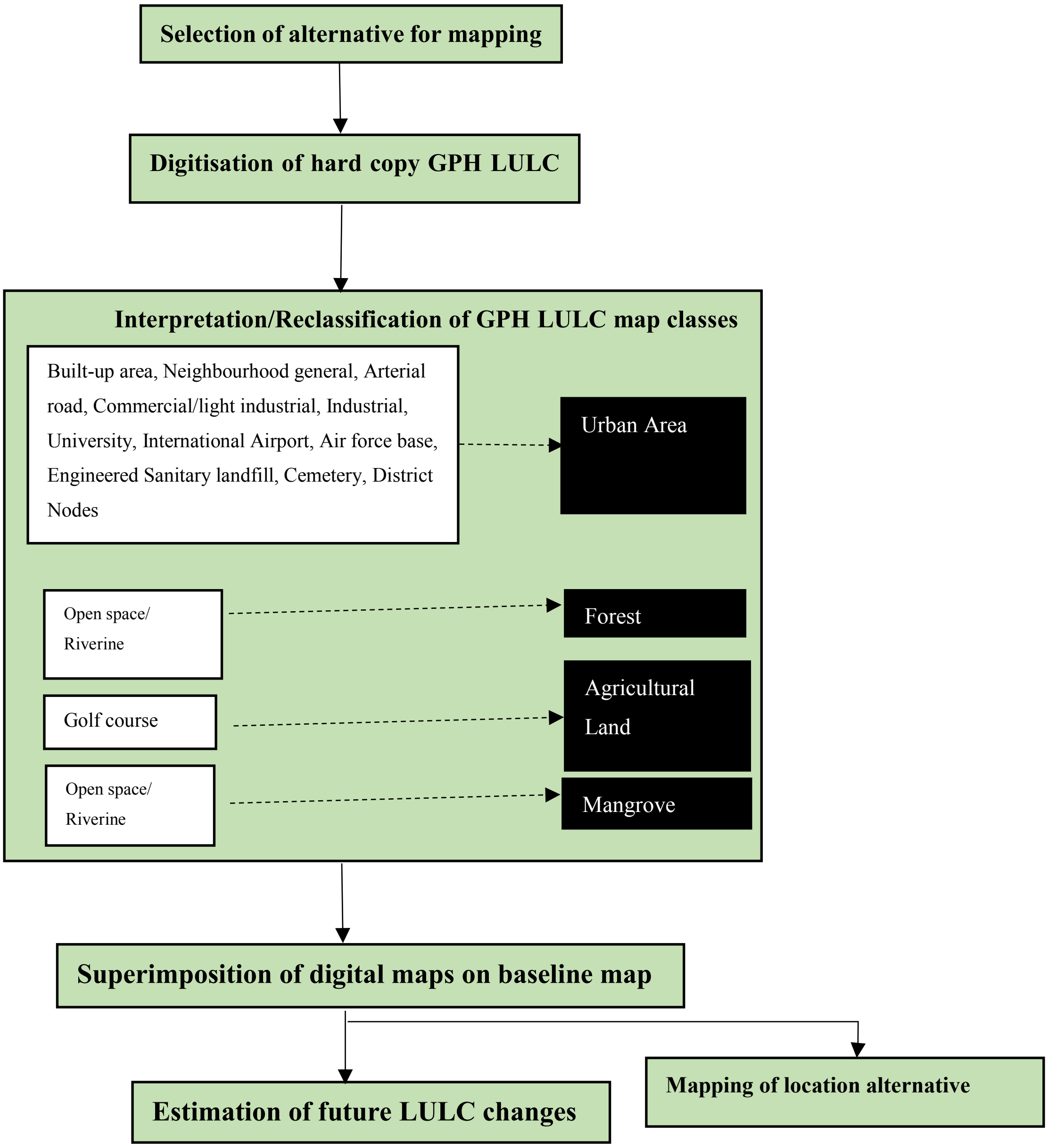


Figure 4.15 Procedure used for mapping alternatives and estimating the future (2060) LULC conditions involving: selection of alternative for mapping, digitisation of hard copy GPH LULC, interpretation/reclassification of GPH LULC map classes, superimposition of digital maps on baseline map, Mapping of location alternative and estimation of future LULC changes.

4. **Overlay of digital maps on baseline map-** The reclassified LULC polygon map was then overlaid on the 2003 baseline map. The erase tool in ArcMap was used to replace

the area of interest (AOI) in the underlying baseline map with the 2060 map. After this step, the total number of LULC became 5 as River class was then added from the baseline polygon LULC map.

5. **Mapping of location alternative**-To create an alternative to the current Phase-1 project, the Phase-1 map was then dragged to the three locations (at Bori, Ogba/Omoku and Port-Harcourt) as specified in the EIS report.
6. **Estimation of future LULC changes**-Finally, changes to future urban LULC due to implementation of the Masterplan as well were estimated and used as input in the hydrologic model.

4.7.2 Future Rainfall and Forest Scenario Construction.

Scenarios simply describes the possible future states of an environment or development (Börjeson *et al.*, 2006). They are also images of future or alternative futures (Alcamo and Henrichs, 2008). Generally, future scenario analysis is essential for reducing uncertainties (Du *et al.*, 2012). They are useful tool for assessing human impacts on the natural environment as well as raising awareness about a new or intensifying environmental problems (Alcamo and Henrichs, 2008). In this study, future afforestation scenarios were used for assessing flood mitigation options in the watershed under study. Rainfall scenarios and afforestation scenarios were used to understand the possible impacts of land-use change on the hydrologic system.

Procedure for Generating Rainfall Scenario.

Three future rainfall scenarios-44yrs, 57yrs and 100yrs return period were developed in this study to examine the watershed response to afforestation in different storm conditions. As shown in Table 5.7, 44yr and 57yr storm scenarios were generated based on the IPCC's SRES A2 and A1B projections downscaled for Nigeria in McSweeney *et al.* (2010) (See McSweeney *et al.* (2010) for more details). The maximum 1-day rainfall values (Table 5.7) were obtained based on A2 and A1B storm projections. A2 describes a very heterogeneous future world with regional economic development and a balanced reliance on fossil and non-fossil energy sources. Under this scenario, storm of 183.7mm was projected against the year 2060. Whereas, A1B describes a future world of very rapid economic growth. Under this scenario, storm value of 208.7mm was projected for the year 2100. 44yr and 57yr return periods were used because they are future predictions based on IPCC projections for the area. 100yr storm is frequently used as design storm (Schanze, 2006; Excimap, 2007; Merz *et al.*, 2007). The 100yr storm rainfall value of 290.1mm was derived using regression analysis and was based on the regression equation performed based on 24 years daily rainfall historical data (Figure 4.16). The 100yr storm was applied as design storm. However, there might be uncertainties due to the number of points in the projection. The steps for deriving the 100yr storm is as follows:

Step 1: Return period was determined using the equations

$$T = \frac{100}{Fa}$$ ***Equation 4.1***

$$Fa\ (\%) = \frac{100(2n-1)}{2y}$$ ***Equation 4.2***

Where n=rank of event; y=total number of events; Fa= Probability of occurrence; T= Return period

Step 2: 100yr storm return period was determined using the regression equation

$$y = 1.905x + 99.59$$ ***Equation 4.3***

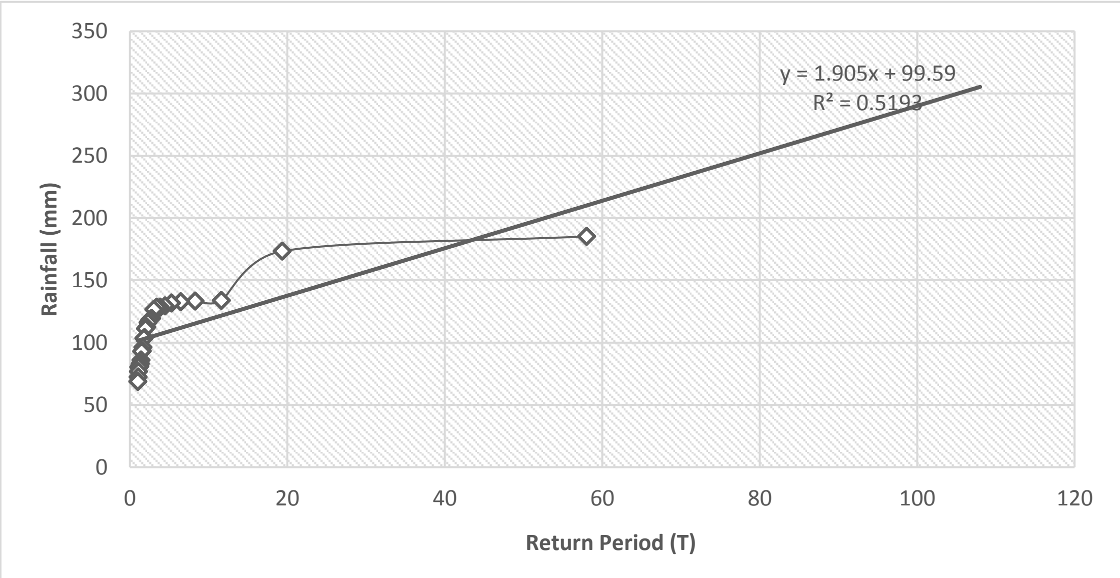


Figure 4.16 Regression analysis trend line used for deriving 100yr storm scenario.

In many countries (for example United Kingdom, Germany, Spain, France, USA, Canada and New Zealand), areas affected by a 100yr flood play is crucial for flood mitigation. Such areas are used for representing medium to extreme flood hazard in flood hazard mapping. Usually floods with a very low probability, e.g. 500yr are extreme event scenarios, whereas floods with a medium probability are likely to have return period ≥ 100yr. Meanwhile, 5yr or 10yr floods are considered frequent events and high probability floods (Schanze, 2006). 100yr floods are used for design and zoning in flood risk management (Excimap, 2007; Merz *et al.*, 2007). In this study, 44yr and 57yr storm floods were used as medium probability while 100yr storm flood was considered high probability storm flood (Table 4.7b). This was reasonable since flood flow largely depends on prevailing storm.

Table 4.7b Future rainfall scenarios used as HEC-HMS inputs.

Return period	Magnitude (mm)	IPCC Carbon Emission scenario	Source	Year predicted against	Description	Return period
T=44yr	183.7	A2	McSweeney et al. (2010)	2060	Heterogeneous world	T=44yr
T=57yr	208.7	A1B	McSweeney et al. (2010)	2100	Rapid economic growth	T=57yr
T=100yr	290.1	Statistically generated	Regression Analysis	2060	Design Storm	T=100yr

Procedure for generating afforestation Scenarios.

Five (5) afforestation scenarios were developed consisting of: Urban Masterplan (UMP) scenario; Urban Masterplan + Urban sprawl (UUMP) scenario; No forest (NF); Low afforestation scenario (LAF); and High afforestation scenario (HAF). Afforestation scenarios were developed to compare the effects of different afforestation scenarios on flooding in the GPH watershed. These effects were assessed under different afforestation and rainfall scenarios.

This afforestation scenario generation was achieved using the following steps below in ArcMap.

1) Firstly, urban Masterplan (UMP) scenario was constructed using the urban Masterplan layout map. In this case, it was assumed that all GPH projects (A, B and C) would go on as planned. Here, the main interest was the urban LULC category and was done by overlaying the GPH urban Masterplan on the 2003 map satellite imagery. It was also assumed that the condition of other LULC categories largely remained the same (See Appendix 6.1).

2) Secondly, Urban Masterplan + Urban Sprawl (UUMP) scenario was constructed (Appendix 6.2). In this case, it was assumed that urban sprawl (60% of additional urban LULC) would accompany the city's growth due to informal settlements in potential growth areas. This figure was based on a previous estimate in Arnott (2008). The study reported that about 60% of housing in low income countries were unauthorized (Arnott, 2008). In addition, the UN estimated that about 60% of urban dwellers live in slums in Sub-Saharan Africa (UN-HABITAT, 2014). This scenario was constructed to assess the effect of future urbanisation on flooding. Location of urban sprawl was placed in the northern part of the watershed based on the idea that developments upstream often have effect on downstream flooding, see (Teng and Chen, 2013; Kuenzer *et al.*, 2015).

Rainfall scenarios	100yr	UMP(100yr)	UUMP(100yr)	NF(100yr)	LAF(100yr)	HAF(100yr)
	57yr	UMP(57yr)	UUMP(57yr)	NF(57yr)	LAF(57yr)	HAF(57yr)
	44yr	UMP(44yr)	UUMP(44yr)	NF(44yr)	LAF(44yr)	HAF(44yr)
		UMP	UUMP	NF	LAF	HAF
			Afforestation scenarios			

Figure 4.17 Matrix of future afforestation and rainfall scenarios used as HEC-HMS inputs. UMP =Urban Masterplan, UUMP=Urban Masterplan + Urban Sprawl, NF=No Forest, LAF=Low Afforestation Scenario, HAF=High Afforestation Scenario.

3) Thirdly, a forest (NF) scenario (based on 0% forest LULC) was generated hypothetically by converting all the forests in the previous scenario to agricultural land. In this scenario it was assumed that all forest were deforested (Appendix 6.3). Hence this scenario was used to assess the effect of % 0 of forest cover on runoff.

4) Fourthly, a low afforestation (LAF) scenario was constructed by increasing the area of forest LULC to 18.35% (Appendix 6.4). In this scenario, it was assumed that about 20 %

of the watershed will be covered by forest (mainly in upstream areas) to assess the effect of forest on runoff.

5) Finally, high afforestation (HAF) scenario was also hypothetically generated by increasing the area of forest LULC from 18.38% to 38.50% (Appendix 6.5). In this scenario, it was assumed that about 40 % of the watershed will be covered by forest (mainly upstream) to assess the effect of forest on runoff.

Note, LAF and HAF scenarios were constructed in upstream parts of the watershed based on the upstream-downstream linkages noted in studies that upstream deforestation, reforestation and afforestation affect downstream flooding (Hofer, 2005; Nepal *et al.*, 2014). It was also constructed based on the notion that afforestation or dense vegetation can help reduce the effect of flooding (CIFOR, 2005).

4.8 PREPARATION OF TOPOGRAPHICAL & SPATIAL INPUT DATA.

Simulating runoff requires a set of data as inputs for modelling. The comprehensive information about HEC-HMS data requirements can be found in USACE (2013). The required data inputs belong to the following category:

1. Topographical data: digital elevation model data (DEM)
2. Spatial data: soil and LULC data

4.8.1 Topographical Data.

In this study, two Shuttle Radar Topography Mission STRM DEM (SRTM: 38_11 and 38-12) map tiles of 90m x 90m resolution were first downloaded from the USGS site (http://srtm.csi.cgiar.org) in Geotiff format. Next, the data were then re-projected from WGS84 geographic projection to WGS84_UTM_Zone_32N projected co-ordinate system. Subsequently, the DEM tiles were then merged, clipped and masked and then used for extracting channel characteristics such as slope, flow paths, centre points and reach lengths for estimating flow. Topographical data were also used for delineating sub-basins. Note that the high resolution DEM (of 1-arc second) available for the United States was not available for the studied area. Only the 3-arc seconds (90m x 90m) data available for the African continent was used.

4.8.2 Spatial Data Set.

Spatial data comprises mainly of soil and LULC data. Soil maps together with LULC maps, were the primary data for generating curve numbers (CN), whereas, LULC maps were used for determining the percentage of impervious area (PctImp) for hydrologic modelling (USACE, 2009).

Generation of Hydrologic Soil Groups from Soil maps

Soil map was one of the primary input for generating SCS curve numbers. There was no readily available soil map for determining Hydrologic soil group (HSG). Hydrologic soil groups of soils represent soils having similar runoff potential under similar storm and land-cover conditions. They determine a soil's associated runoff curve number (USDA, 2014). The runoff curve numbers are used to estimate direct runoff from rainfall. To generate soil data the following procedure was followed:

1. First, a 1:1,000,000 digital soil map was obtained from the United Nation's Food and Agricultural Organisation (FAO). See Appendix 4.2.
2. Then the map was clipped and re-classified based on soil texture of which two types of soil were identified (clay and sandy clay). As such two types of HSG was were categorised in the area (see Table 4.8).

Generally, there are four types of HSG soil groups (A, B.C and D), and runoff potential increases from A to D (USDA, 1986; Feldman, 2000). **HSG A** soils have an infiltration rate greater than 0.3 in/hr and are predominantly sand or gravel soils with low runoff potential. **HSG B** are soils characterised by infiltration rates ranging from between 0.15 to 0.30 in/hr and are moderately coarse soils. The infiltration rate of **HSG C** soils ranges from 0.05 to 0.15 in/hr and are moderately fine to fine soils that can impede water flow. For **HSG D,** the infiltration rate is less than 0.05 in/hr and are typically very fine soils (clays) with high runoff potential (Feldman, 2000; Washburn *et al.*, 2010). Note, this study area was mainly covered with C (sandy clay) and D (clay) soils. That is with soils characterised by low and very low infiltration rates.

Table 4.8 Hydrologic Soil Group Classification for the Study Area. This study area was mainly covered with C (sandy clay) and D (clay) soils.

FAO's soil type	Texture	HSG code	Infiltration rate
Fluvosol	Clay	D	Very low
Gleysol	Clay	D	Very low
Ferrosol	Sandy clay	C	Low

Curve Number Generation from Soil and LULC Data.

The Natural Resources Conservation Service's Runoff Curve Number (CN) is an empirical parameter used for predicting infiltration and direct runoff from rainfall. CN is an index that represents the runoff potential of a sub-basin (Feldman, 2000). After generating the HSG data, the CN number was determined from the combination of LULC maps and a soil map (Feldman, 2000).

1. All LULC raster maps were converted to polygon maps and assigned land-use codes based on the LULC type. Note in hydrology: water and mangrove classes are assigned very high runoff potential. Therefore, both land-cover types were re-classified to as waterbody due to similarity in their hydrologic properties.

Table 4.9 Land-use/land-cover code in the attribute table used for Hydrological modelling.

LULC classification	LULC code	PctImp (%)
Urban	1	54.3
Forest	2	7.8
Agricultural land	3	9.0
Waterbody	4	2.9

2. Next, depending on the HSG and LULC type, CN values were assigned. Note: CN values were assigned using NRCS runoff CN values in Table 4.10 based on values in Table 2-2a to Table 2-2b in USDA (1986). That is for urban areas, forest, agricultural land and waterbody. The higher the CN value, the greater the runoff potential.

Table 4.10 CN Look-up Table Generated for HMS Modelling (USDA, 1986).

LULC	LU value	A	B	*C	*D
Urban	1	77	85	90	92
Forest	2	30	55	70	77
Agriculture	3	43	65	76	82
Waterbody	4	100	100	100	100

3. Finally, after merging the land-use and soil group layer, a Look-up table was further generated. The Look-up table was then used to create a CN-grid map in HEC-GeoHMS. Appendix 6.8 shows an example of a CN grid map generated as input for modelling.

4.9 RUNOFF ESTIMATION USING HYDROLOGIC MODELLING TECHNIQUE.

4.9.1 Overview.

The goal of this section was to describe and justify the hydrologic modelling method used for estimating peak flow. Another important goal was to describe the steps followed in modelling the GPH watershed. This section is generally structured into model description and modelling procedure. First, available hydrologic models were discussed and compared. Next, the HEC HMS model was justified and described. Afterwards, the detailed steps followed in the method were described including, pre-processing, model construction and model validation.

4.9.2 Hydrological Modelling.

Hydrologic (rainfall-runoff) modelling is a simplified representation of a complex hydrologic system (Figure 4.18). It involves the approximation of the actual system. Its inputs (e.g. rainfall) and outputs (e.g. flow) are measurable hydrologic variables, whereas, its structure embroils the concept of system transformation (Xu, 2002). Hydrologic models have been developed for a variety of reasons, but commonly used to meet two primary goals. First, to gain better understanding of the hydrologic phenomena operating in a catchment. Second, to generate hydrologic data for design and flood forecasting purposes (Horritt and Bates, 2002; Xu, 2002; Im *et al.*, 2008; Du *et al.*, 2012). Moreover, in time past, they have been used for scientific research, data collection, watershed management and land-use planning purposes (Xu, 2002; Reddy, 2005; Davie, 2008). Like other physical processes, hydrologic systems, as a whole, are extremely complex to understand and control, however, some aspects can be better understood if approached by abstraction (Xu, 2002; Sorooshian *et al.*, 2009). In this study, the hydrologic modelling method was used to address the research question: *What are the effects of historical and future urbanisation and climate change on runoff in the entire basin.* It was used to understand the watershed's response to extreme rainfall and land-use changes.

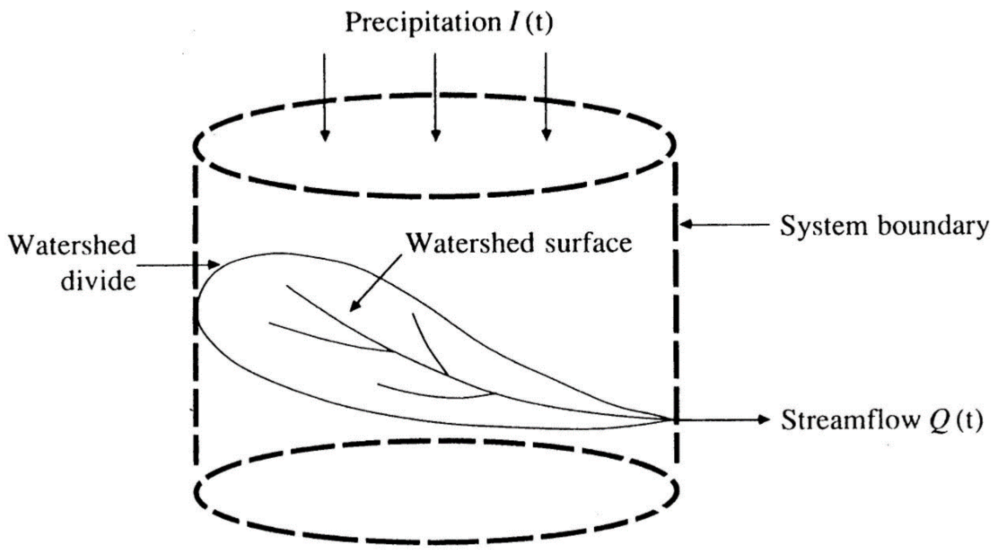


Figure 4.18 A simplified representation of a hydrologic system (Knapp *et al.*, 1991).

Classification of Hydrologic Models.

Hydrologic models can be classified in various ways. Various classifications in studies depended on the criteria of interest (Knapp *et al.*, 1991; Davie, 2008; Beven, 2012a). Classification was done in this study to discuss and describe strengths and limitations. Hence, hydrologic models can be classified as: (1) Event and Continuous Simulation Models, (2) Empirical, Conceptual and Theoretical Models, (3) Lumped and Distributed Parameter Models, 4) Physically-based (white-box) and Empirical (black-box) Models (Knapp *et al.*, 1991; Xu, 2002; Sorooshian *et al.*, 2009). Hence, the distinction between the lumped and distributed model is the most important classification expressed in the study.

Lumped models consider the entire river basin as one unit, disregarding spatial variability. The model relates the forcing data (mainly, precipitation inputs) to system outputs (streamflow) without spatial discretization. Meanwhile, a distributed model accounts for spatial variations of variables and parameters, resulting in explicit characterisation of the processes and patterns (Knapp *et al.*, 1991), see Figure 4.19. A lumped model is useful for estimating flow, but just at the watershed outlet. It cannot be used to forecast floods in real time (Knapp *et al.*, 1991; Sorooshian *et al.*, 2009). Nonetheless, they can be made to act like distributed parameter models by adopting a detailed database and by segmenting the watershed into smaller sub-basins, termed a semi-distributed model (Nix *et al.*, 1991; Sorooshian *et al.*, 2009). So far, lumped models have been developed and successfully applied in different models including: the Crawford and Linsley's Stanford Watershed Model (1962), Xinanjiang Model (Zhao *et al.*, 1980), US National Weather Service (NWS) for flood forecasting, and the Sacramento Soil Moisture Accounting Model (SAC-SMA), (Xu, 2002; Sorooshian *et al.*, 2009).

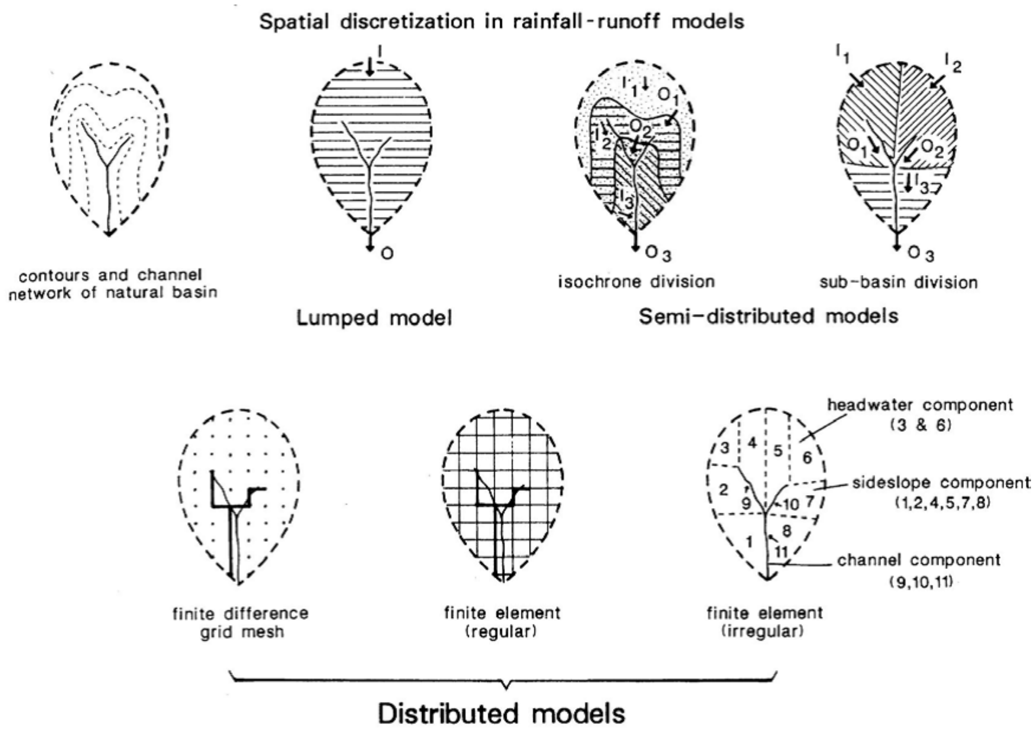


Figure 4.19 Graphical representation of geometrically distributed models, semi distributed models and lumped models. I=input and O=Output (Source: Jones, 1997 in Xu, 2002).

Distributed models uniquely consider the main model parameter variations to evaluate the influence of the distribution on simulated behaviour (Xu, 2002; Sorooshian *et al.*, 2009; Beven, 2012b). Several studies agree that distributed models increase accuracy of simulation (Xu, 2002; Sorooshian *et al.*, 2009; Beven, 2012b). This accuracy is said to emanate from preserving the distribution of all spatial and non-uniform hydrologic processes (Xu, 2002; Sorooshian *et al.*, 2009), hence, making the model a more reliable representation of the real world than a lumped model (Sorooshian *et al.*, 2009). To date, several distributed models have been developed and successfully implemented, including: Système Hydrologique Européen (SHE) model (Abbott *et al.*, 1986a, and b), TOPMODEL (Beven and Kirby, 1976, 1979), and MIKE SHE (Refsgaard and Storm, 1995). Nevertheless, the distributed model is associated with huge limitations, principally, the amount of data required to set the initial conditions and parameterize the model is enormous (Sorooshian *et al.*, 2009). Secondly, in theory, calibration is not needed for a spatially distributed model and values of the parameter can be obtained, but this is not the case in reality. For example, the idea of obtaining saturated hydraulic conductivity measurements for every grid point in a catchment is unrealistic (Sorooshian *et al.*, 2009). Consequently, the lack of data to run the model may lead to spatial averaging of parameters (Davie, 2008). If data is lacking, a distributed model may deteriorate into a lumped system model (Davie, 2008).

Theoretical models, called white-box models, or physically-based models, have a logical structure similar to the real-world system (Xu, 2002). They are developed based on physical laws governing the phenomena for example, the runoff models based on St. Venant's equations (Xu, 2002). Empirical models are referred to as black-box models or input output models. Black-box models rely upon a statistical correspondence between the model input (rainfall) and model output (runoff) without relating it to the underlying physical processes (Knapp *et al.*, 1991). They consist of parameters that may have little direct physical significance (Xu, 2002). One example of an empirical approach to predicting runoff from rainfall is the Curve Number (CN). Moreover, regression is also used to derive relationships. Another example is the unit hydrograph method. According to Xu (2002), empirical models provide more accurate answers and are valuable for decision-making. Meanwhile, conceptual models, referred to as so-called grey-box models, are intermediate between theoretical and empirical models. In terms of timing, event models typically estimate the runoff from a single storm event, describing a relatively short period within the hydrologic record (Knapp *et al.*, 1991). On the other hand, continuous simulation models operate for a longer period, which includes rainfall events and inter-storm conditions (Knapp *et al.*, 1991).

4.9.3 HEC-HMS Model.

In order to address the research question (RQ2), the Hydrologic Engineering Centre's Hydrologic Modelling System software (otherwise known as the HEC-HMS) version 4.0, was used to couple rainfall-runoff models adopted for this study. The HEC-HMS developed by the US Army Corps of Engineers (USACE) is designed to simulate the rainfall-runoff (R-R) process in watershed systems (USACE, 2009, 2013). The model has the capacity to estimate peak discharge, peak volume, and time to peak, given the precipitation, soil and land-use inputs (Feldman, 2000; Scharffenberg and Fleming, 2006; Oleyiblo and Li, 2010; Suriya and Mudgal, 2012; Tripathi *et al.*, 2014). Hydrographs generated by the program can be used in this and other programs to study future urbanisation impact, flood damage, urban drainage, flow forecasting and so forth. The program has been extensively used for addressing flood frequency, flood warning systems, planning, reservoir spillway capacity and stream restoration (Feldman, 2000; Chen *et al.*, 2009; Du *et al.*, 2012; Suriya and Mudgal, 2012; Tahmasbinejad *et al.*, 2012; Halwatura and Najim, 2013; Sanyal *et al.*, 2014). In this study, the model was useful for simulating the rainfall-runoff-routing process for analysing historic and future changes to flooding within the GPH watershed.

The program has an extensive array of functions mainly: watershed description, meteorology description, parameter estimation, simulation analysis and GIS connection (USACE, 2009, 2013). Moreover, the program has four important components including: an analytical model for simulating flow and routing; an advanced graphical user interface (GUI) for visualising output, data management and storage system as well as a reporting system (USACE, 2009; Halwatura and Najim, 2013; USACE, 2013). Figure 4.20 below presents the model description and the work flow of the model application from model pre-processing, model run and finally, to model validation.

4.9.4 Rationale for using HEC-HMS Software.

The selection of the HEC-HMS software was mainly based on the objectives of this study and available data. The rationale for selection includes:

1. **Wide geographical application.** HEC-HMS model has extensively been applied in a wide range of geographical areas and contexts. Importantly, it has been used for modelling rainfall-runoff in tropical catchments. For example, it was used for estimating flow in the Marikina River in the Philippines (Abon *et al.*, 2011);

Attanagalu Oya catchment in Sri Lanka (Halwatura and Najim, 2013); Una river basin in Brazil (Neto *et al.*) and the Skudai River in Johor, Malaysia (Yusop *et al.*, 2007).

2. **Extensive application.** The model has been extensively used to analyse the impacts of urbanisation on flooding in different parts of the world. It has been used to model flood events in the Qinhuai River Basin, China (Du *et al.*, 2012). It has also been applied to study the impacts of land-use change on surface runoff of the Lai Nullah Basin in Islamabad (Ali *et al.*, 2011). Chen *et al.* (2009) applied the model in combination with other software for predicting urban land use scenario changes and possible hydrologic changes. Knebi et al. (2005) applied the model in a similar regional study.
3. **Ability to handle spatial variations and single event**. Thirdly, the HEC-HMS contains semi-distributed models (except ModClark). With these models, watersheds are divided into sub-watersheds and their spatial variations are averaged (Ali *et al.*, 2011). HEC-HMS also contain event scale models capable of simulating single storm events.
4. **Ability to model a wide range of hydrologic processes**. The model takes into account every hydrologic process from losses (such as evaporation, evapotranspiration, surface storage, interception and infiltration) to surface runoff to base flow (Feldman, 2000). A range of methods can be selected for calculations, including the SCS curve number or Green and Ampt infiltration, Clark, Snyder or SCS unit hydrograph methods and lag routing methods.
5. **The ability to estimate peak discharge in ungauged basins.** Catchments in the study area are ungauged which is a challenge for hydrologic studies. The HMS model is capable of simulating the rainfall-runoff process in ungauged basins where input and calibration data are unavailable (Sanyal *et al.*, 2014). The software contains measured parameter models which are capable of estimating parameters from system properties (Feldman, 2000).
6. **Reliability, cost and input complexity**. Lastly, storm water program such as info works and civil storm are not found in the public domain but HEC–HMS can be found in the public domain and is at the same time reliable (Halwatura and Najim, 2013; MPCA, 2015). In terms of input complexity, HEC-HMS has a medium input complexity while other software such as SWAT and Mike URBAN have high input complexity. This means the latter are more data intensive. Moreover, compared to HEC-HMS, SWMM is more data intensive (MPCA, 2015).

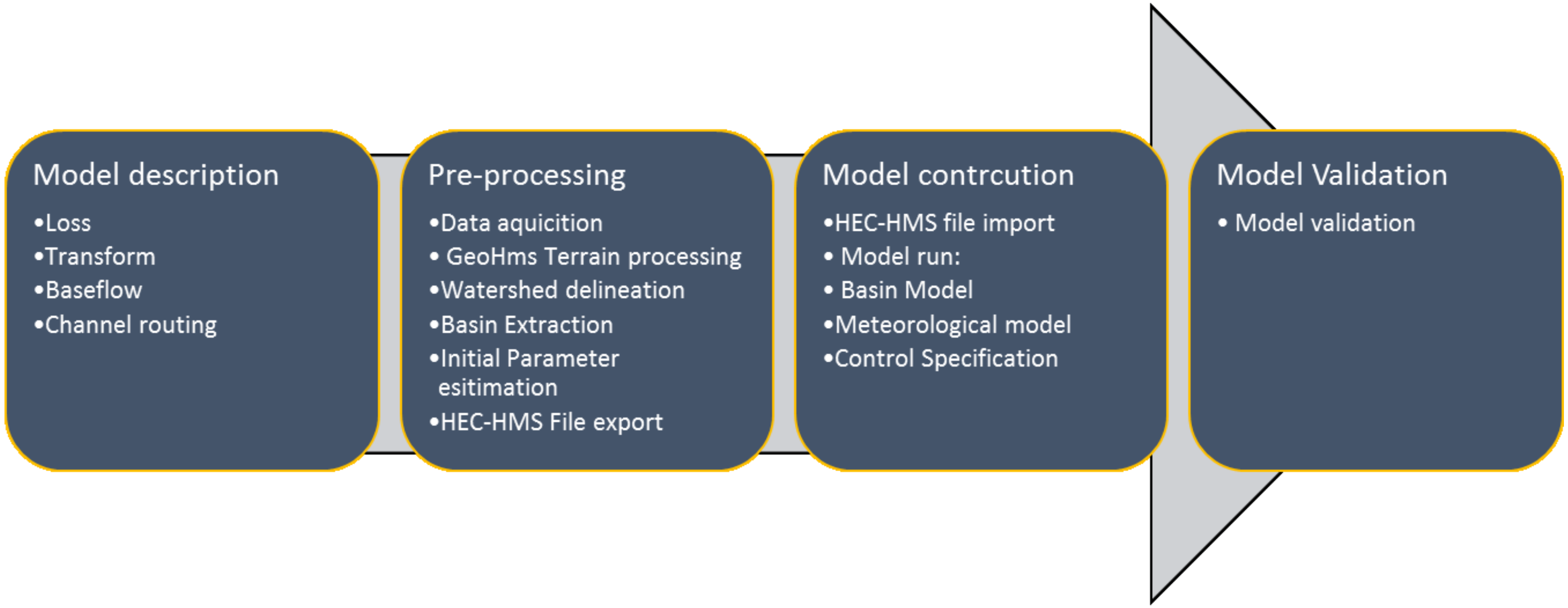


Figure 4.20 Flow chart of the Hydrologic modelling process. Four main stages were involved including: Model description, Pre-processing, Model construction and Model validation.

4.9.5 HEC HMS Model description.

The hydrologic model used in this study (HEC-HMS) is a physically based, semi-distributed model, designed to simulate rainfall-runoff (R-R) processes, as shown in the simplified model in Figure 4.21. HEC-HMS combines separate models to represent the components of the rainfall-runoff process. It estimates loss (runoff volume), transformation (discharge runoff), base flow and channel routing respectively.

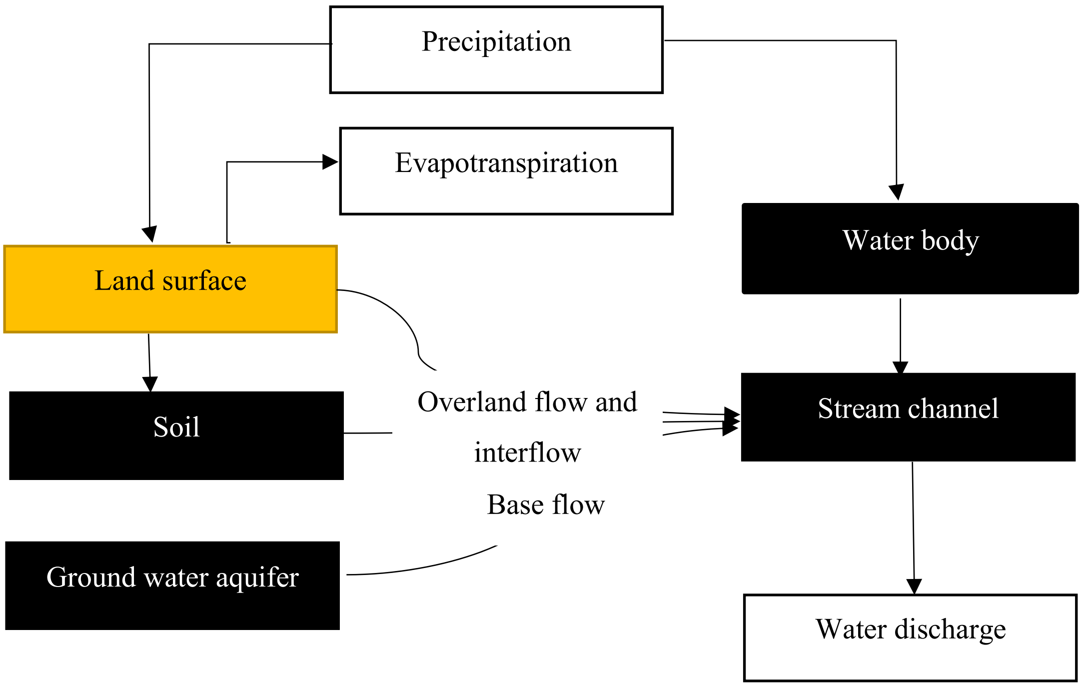


Figure 4.21 Simplified diagram of the hydrologic processes modelled with HEC-HMS. Source: Feldman (2000).

The Basin Model is used to represent the physical process of the watershed, comprising of the basin and channel routing parameters as well as connectivity data. The Precipitation Model contains the rainfall inputs in the model, while the Control Model is used to regulate the duration in the model. The time series data set contains rainfall gauge time series data. After the model run, the process was completed by validation. More details of the modelling processes are given in the user's manual and technical reference manual (Feldman, 2000; USACE, 2013). In this study, historical and future peak discharge values were determined based on climate change and land-use scenarios. Due to lack of calibration data, validation was done using the alternative Prediction in Ungauged Basins, or PUB, approach. The results were then used as inputs in the HEC River Analysis System (HEC-RAS) to compute water surface profiles (WSF) and other outputs for flood inundation maps.

The Hydrograph.

The hydrograph in Figure 4.22 is a graphical representation of the instantaneous discharge of a stream flow plotted with time. (Heggen *et al.*, 1996; Raghunath, 2006). That is a plot of flow with respect to time. It includes the contributions from channel precipitation, surface runoff, groundwater seepage and drainage. The shape of the hydrograph varies depending on controlling factors in the drainage basin, but generally includes components such as the rising limb, recession limb, peak discharge or flow, direct runoff and baseflow. The rising limb represents a portion of the hydrograph where runoff is increasing, first as surface runoff and later, throughflow. Peak discharge refers to the point of the hydrograph with the highest flow (Heggen *et al.*, 1996; Feldman, 2000).

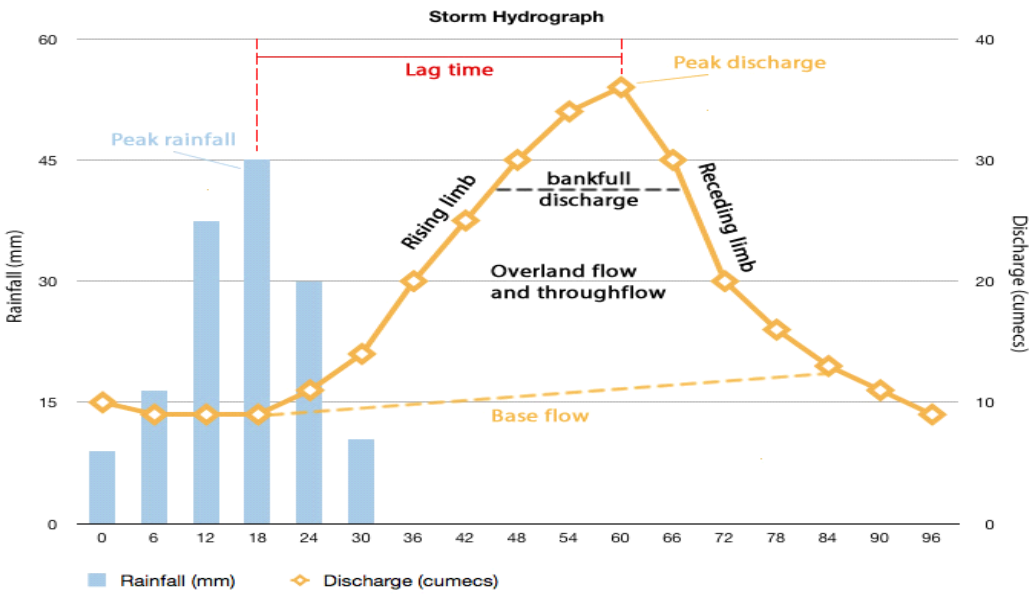


Figure 4.22 Graph showing the different components of a storm hydrograph.

Lag time or basin lag, is the time difference between the peak of the rain event and the peak discharge. The falling, or recession limb refers to the portion of the hydrograph where runoff is decreasing. The baseflow represents the normal daily discharge of the river and results from groundwater seeping into the river channel (Heggen *et al.*, 1996; Feldman, 2000).

It is worth noting that, two main measures are generated as output in the HEC-HMS model, including: Peak flow and Time to Peak. These are often the key parameters used for the design and analysis of urban hydrologic systems (Feldman, 2000; Blick *et al.*, 2004). **Peak flow** (Q_P) expressed in m^3/s is the main parameter used for analyzing runoff (Ali *et al.*, 2011; Verbeiren *et al.*, 2013; Sanyal *et al.*, 2014) and refers to the point of the hydrograph with the highest flow. **Runoff volume** (in mm) is estimated from precipitation-excess which occurs when the rate of rainfall exceeds the rate infiltration into the ground. **Time to peak (T_P)** is the time from the centre of mass of the rainfall to the peak of the hydrograph (Feldman, 2000; USACE, 2009).

Peak discharge and runoff volume are affected by the intensity and duration of the rainfall. Runoff volume, or amount of runoff, is affected by permeability and porosity of soils and antecedent moisture content. Highly porous or permeable soils can rapidly infiltrate rainfall and generally produce less runoff volume than soils with low porosity and permeability (Blick *et al.*, 2004; Reddy, 2005). Hence, high intensity rainfall in general produces a higher peak discharge than lower intensity rainfall with longer duration. Dense vegetation usually intercepts rainfall and increases infiltration (loss), thereby, reducing runoff volumes and rates. Impervious areas, such as parking lots, roads and rooftops, increase runoff volume and rates by preventing infiltration. Sub-basins with higher peak runoff rates generally produce shorter time of concentration than those with lower peak runoff rates (Blick *et al.*, 2004; Reddy, 2005).

The Loss Model

In this study, the SCS-CN loss model was used to simulate runoff volume or precipitation excess as a function of cumulative precipitation, land-use, soil cover and antecedent moisture (Feldman, 2000; Du *et al.*, 2012; Halwatura and Najim, 2013). There are a variety of loss models as described in Table 4.11, but the empirical SCS-CN method was adopted for computing infiltration loss in this study. This was because it relies on just one parameter and is less data intensive. It is also reliable, easy to use and has been extensively applied in studies (Feldman, 2000; Bo *et al.*, 2011). The lumped method requires percentage of impermeable surface data for each sub-basin, as well as length of river and elevation of the sub-basins (Zhan and Huang, 2004; El-Hames, 2012; Sanyal *et al.*, 2014; Biddoccu *et al.*, 2016). The underlying theory is that runoff can be related to soil-cover complexes and rainfall through a curve number (Bo *et al.*, 2011)

The SCS CN was estimated using the following empirical relationships

$$Q = \frac{(P-I_a)^2}{P-I_a+S}$$ ***Equation 4.4***

$$I_a = 0.25$$ ***Equation 4.5***

The maximum retention (S) was calculated with the equation:

$$S = \frac{25{,}400 - 254CN}{CN}$$ ***Equation 4.6***

Substituting Eq. 4.5 into Eq. 4.4 and this gives:

$$Q = \frac{(P - 0.25)^2}{P + 0.8S}$$ ***Equation 4.7***

Where Q=runoff; P= accumulated rainfall depth at time t; *Ia* = the initial abstraction (or initial loss); and S = potential maximum retention. Note: the CN (curve number) is an index that characterizes the combination of the land-use classes, the hydrologic soil group (HSG) and antecedent moisture conditions (AMC), (Feldman, 2000; Du *et al.*, 2012). The model assumes that the ratio of actual soil retention after runoff begins when potential maximum retention is equal to the ratio of direct runoff of rainfall (Bo *et al.*, 2011: page 739).

Table 4.11 Attributes of different loss methods in Feldman (2000).

	METHODS	GROUPINGS
1	Initial and constant rate	Event, lumped, empirical, fitted parameter
2	SCS curve number (CN)	Event, lumped, empirical, fitted parameter
3	Gridded SCS CN	Event, distributed, empirical, fitted parameter
4	Green and Ampt	Event, empirical, fitted parameter, distributed
5	Deficit and constant rate	Continuous, lumped, empirical, fitted parameter
6	Soil Moisture accounting	Continuous, lumped, empirical, fitted
7	Gridded SMA	Continuous, distributed, empirical, fitted parameter

Runoff Model

Direct runoff is the principal component of the hydrologic system under study. For modelling runoff transformation, the SCS dimensionless unit hydrograph (UH) was the empirical model used. The model was based on the unit hydrograph theory. Figure 4.23 presents a unit discharge hydrograph resulting from one inch of direct runoff, distributed uniformly over the watershed resulting from a rainfall of a specified duration. The SCS UH model is a dimensionless single-peaked UH and expresses the UH discharge as the ratio to peak discharge (QP), for any given time t, a fraction of Time of UH peak (Tp). By using the SCS DUH, the objective was determined with three variables: Lag time L (hr.), Time to peak, T_p (hr), and

Peak discharge, q_P (m^3/s). In using this method, implicit assumptions of linearity and time-invariance were made as stated in Feldman (2000).

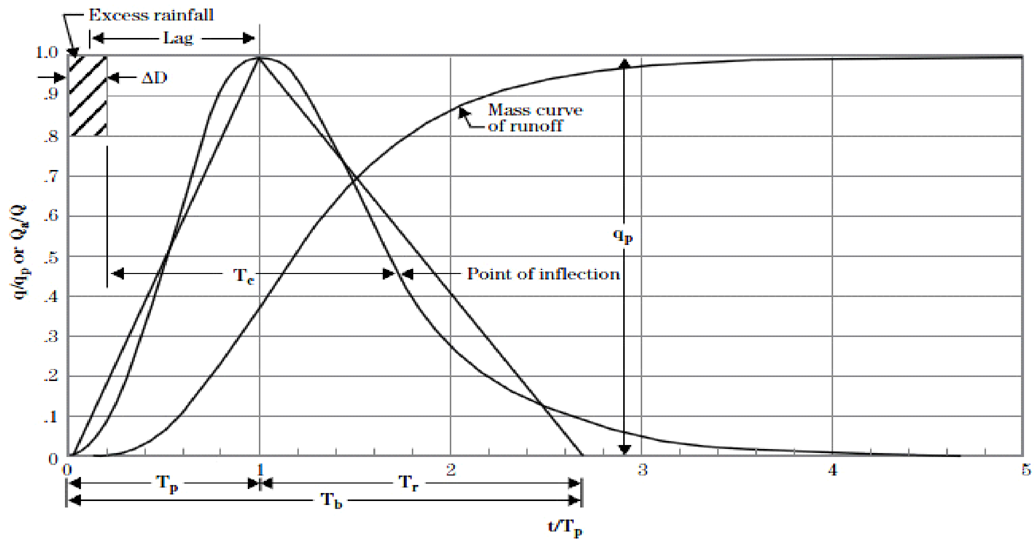


Figure 4.23 SCS Unit Hydrograph.

The NRCS proposes that UH peak (q_P) and time of UH (T_P) peak are related by:

$$q_p = 2.08\left(\frac{A*Q}{T_p}\right) \qquad \textit{Equation 4.8}$$

Where, A=Watershed Area;

A = the drainage area, Q = the runoff volume (excess rainfall) (derived from Eq.4.7)

T_P = the time to peak in hours, and q_P = the peak flow

Time to peak or time of rise equals to the duration of the unit excess precipitation Δt given by the following equation.

$$T_p = \frac{\Delta t}{2} + t_{lag} \qquad \textit{Equation 4.9}$$

Where Δt = excess precipitation duration (which is the coputaional interval in HMS)

t_{lag}= the basin lag

The basin lag is defined as the time difference between peak rainfalls and peak discharge

Note: lag time is the only parameter in this method which was automatically calculated in the model. When the lag time is specified HMS solves equation 4.5 and 4.9

Basin lag time was solved by:

$$T_{lag} = 0.6T_c$$ ***Equation 4.10***

$$Tc = t_{sheet} + t_{shallow} + t_{channel}$$ ***Equation 4.11***

In this project, lag parameter values were derived from T_c computed and was calculated automatically using values of slope and maximum flow lengths derived from the DEM. Lag parameter was imported into the basin model and was then computed for all sub-basins. The SCS dimensionless UH was used because it requires fewer input data and is suitable for estimating peak discharge in ungauged watersheds (Feldman, 2000; USACE, 2013).

Base flow.

Base flow was neglected in this study in the absence of available records. Although this may reduce the accuracy of the result, however Feldman (2000) supports that the contribution of base flow in urban watersheds is negligible and can be neglected.

Channel Routing.

Channel routing is the movement of a flood wave through a river reach (Heimhuber, 2013). A number of routing models are available in HEC-HMS, including Lag, Muskingum, Modified, Modified Puls, Kinematic-wave and Muskingum-Cunge methods. Each of these models solve the continuity and momentum equation and all require basic information such as channel description, energy loss model parameters, initial conditions and boundary condition information. In the absence of calibration data, the Muskingum-Cunge method was selected for routing flow along river reaches. Unlike the Muskingum method, the Muskingum cunge model uses the relationship between channel properties and parameters (Song *et al.*, 2011). It is a suitable alternative for determining parameters X and K and for simulating open channel discharge downstream in ungagged river channels (Roy and Mistri, 2013).

It is solved by simple finite difference and continuity equation given by:

$$\left(\frac{I_{t-1}+I_t}{2}\right) - \left(\frac{Q_{t-1}+Q_t}{2}\right) = \left(\frac{S_t-S_{t-1}}{\Delta t}\right)$$ ***Equation 4.12***

Where I = Inflow; Q = Outflow; S = Storage; and t/Δt = time/ incremental time step.

Storage in the reach is modelled as an aggregation of the prism and wedge storage as shown in 4.24. Prism storage represents the volume shaped by steady-state water surface profile (WSP) and wedge storage is the additional volume right under the WSF of the flood wave.

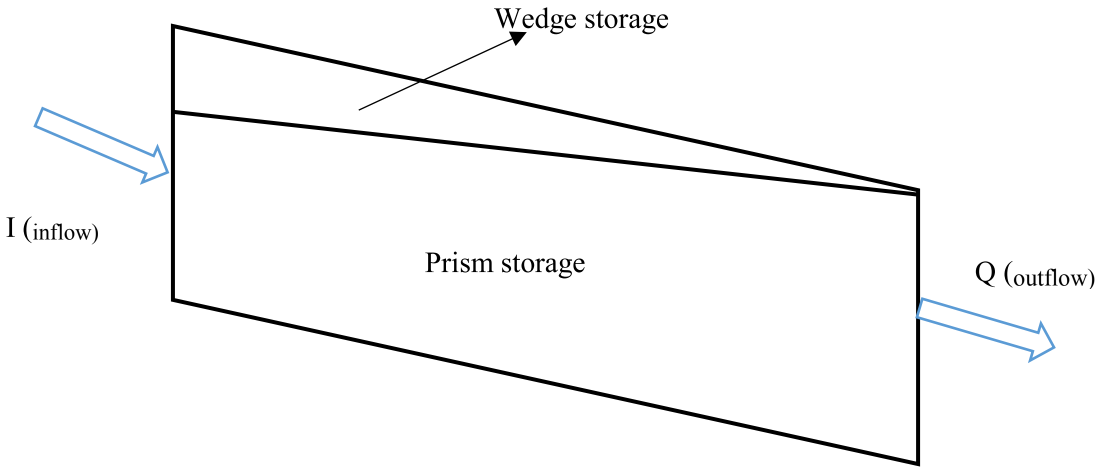


Figure 4.24 Muskingum approximation of storage (Chow et al, 1988).

The Muskingum model defines the storage as:

$S_t = KO_t + KX(I_t - Q_t)$ ***Equation 4.13***

Prism storage is given as:

$S_t = KO_t$ (a linear reservoir model) ***Equation 4.14***

Where: K = flood wave time travel through reach and Q_t = outflow rate.

Wedge storage is given as:

$KX(I_t - Q_t)$ ***Equation 4.15***

Where: X =dimensionless weight $0 \leq X \leq 0.5$

In the Muskingum model, K can be determined if observed inflow and outflow data are available (Feldman, 2000; Song *et al.*, 2011). Once K is estimated, X can be estimated by trial and error, but because the gauge flows required for calibration were not available for the area, the Muskingum-Cunge method was used where K and X where determined from channel characteristics. However, in HEC-HMS, the majority of the steps required for deriving K and X input parameter estimation are automated. The only input parameters required were: channel geometry information such as channel slope, length, shape, bottom width, slide slope derived from the DEM in addition to channel roughness co-efficient (Manning's N) derived from the land-cover attribute table. This method was selected because it is a physically based method. Unlike the other methods, parameters can be estimated from channel characteristics.

4.9.6 Model Pre-processing

Prior to the model application, a series of pre-processing tasks were performed with the input data using HEC-GeoHMS and Arc-Hydro in the ArcGIS environment. HEC-GeoHMS is a Hydrologic Engineering Centre's geospatial modelling extension. The Watershed pre-processing tasks performed is illustrated below in Figure 4.25 and can be divided into 5 major steps including terrain processing, watershed delineation, basin extraction, initial parameter estimation and File export (USACE, 2009). HEC-GeoHMS was ultimately used to generate input files into Hec-HMS for hydrologic simulation.

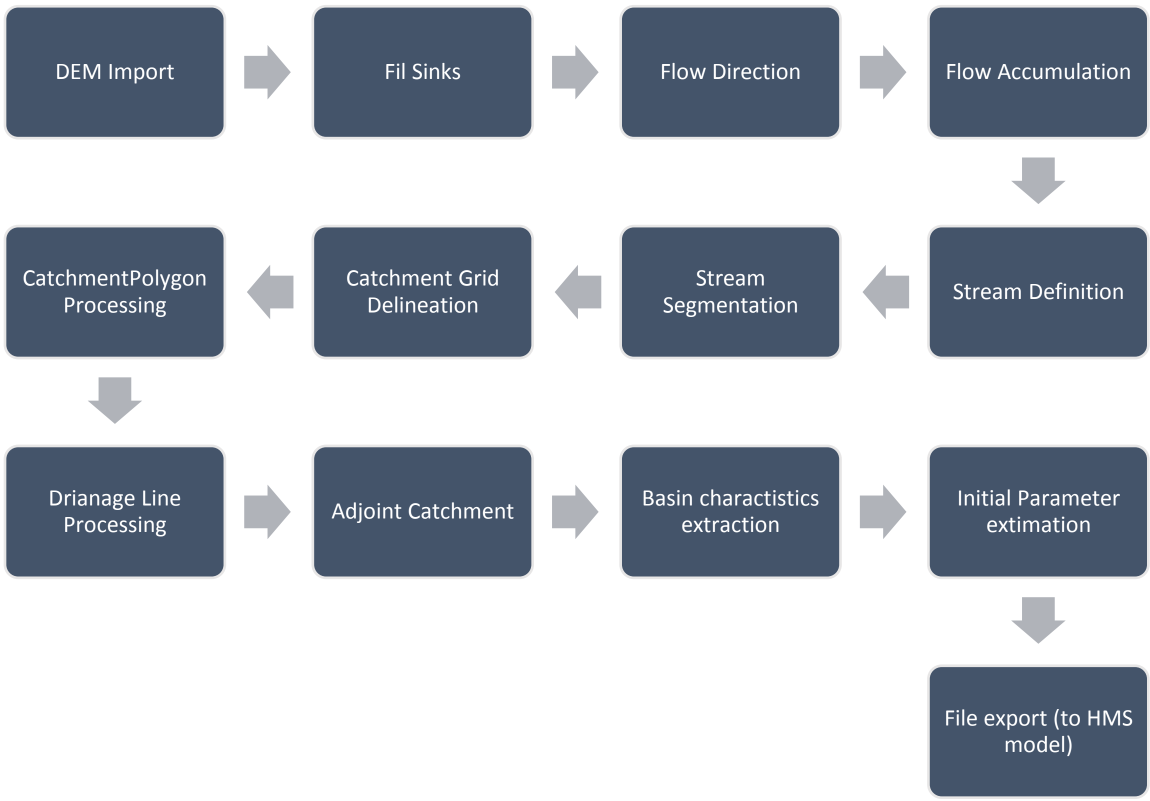


Figure 4.25 Diagram showing Hec-HMS pre-processing steps in HEC-GeoHMS.

4.9.7 Model Pre-processing Procedure

A. Terrain Processing

Terrain processing consisted of a series of steps used to derive the drainage network and create catchment from the DEM. They include sink filling, flow direction, flow accumulation and stream definition. All steps were performed in sequential order as specified in (USACE, 2009; Merwade, 2012b, a).

1. **Fill Sink GRID:** First the Fill Sink was performed. It is reconditioning function and was applied to correct the imported DEM. As a result, a depression DEM was created by modifying cells (surrounded by cells of higher elevation) to the elevation of a surrounding cells, so that water can flow easily. The input was the original DEM and the output was the Agree DEM (fill) as shown Figure 4.26.

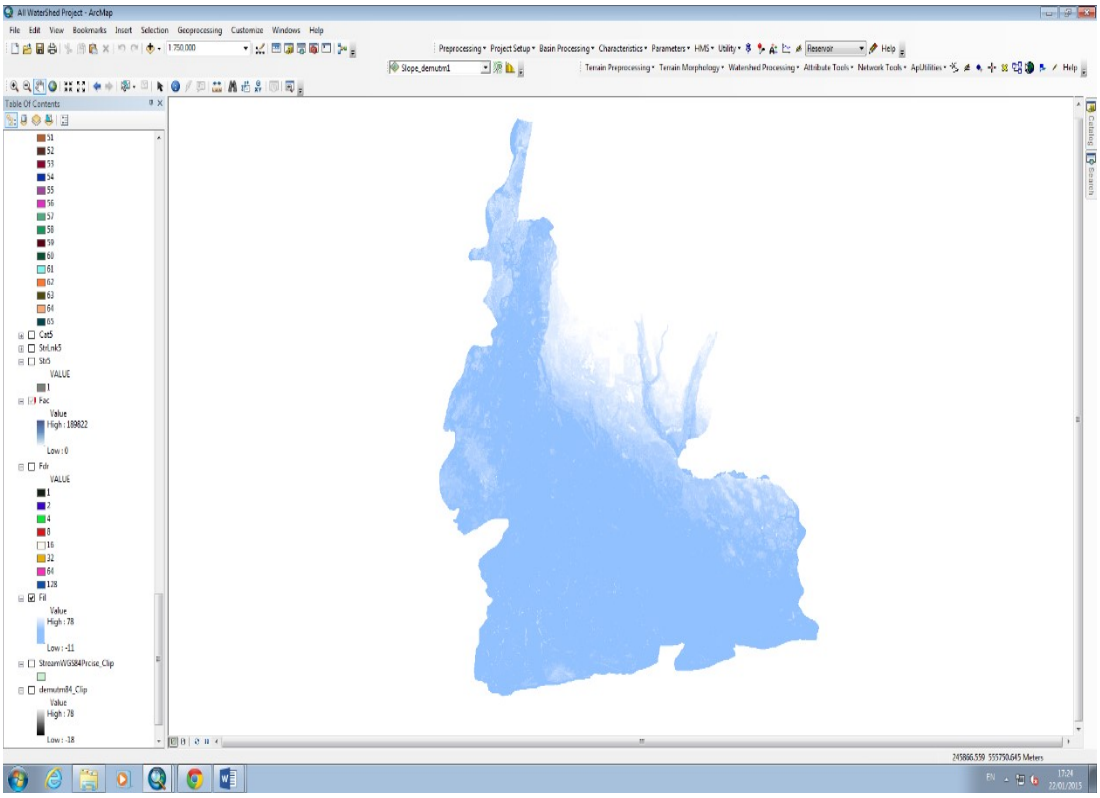


Figure 4.26 Map of the digital elevation model with Sink-fill.

2. **Flow Direction (Fdr) GRID:** The Fdr GRID was delineated from the Sink Fill GRID and is an input to the flow accumulation GRID. This function calculates the flow direction for a given grid (Figure 4.27). Values in the cells of the flow direction grid, specify the direction of the steepest descent from that cell (Merwade, 2012b).

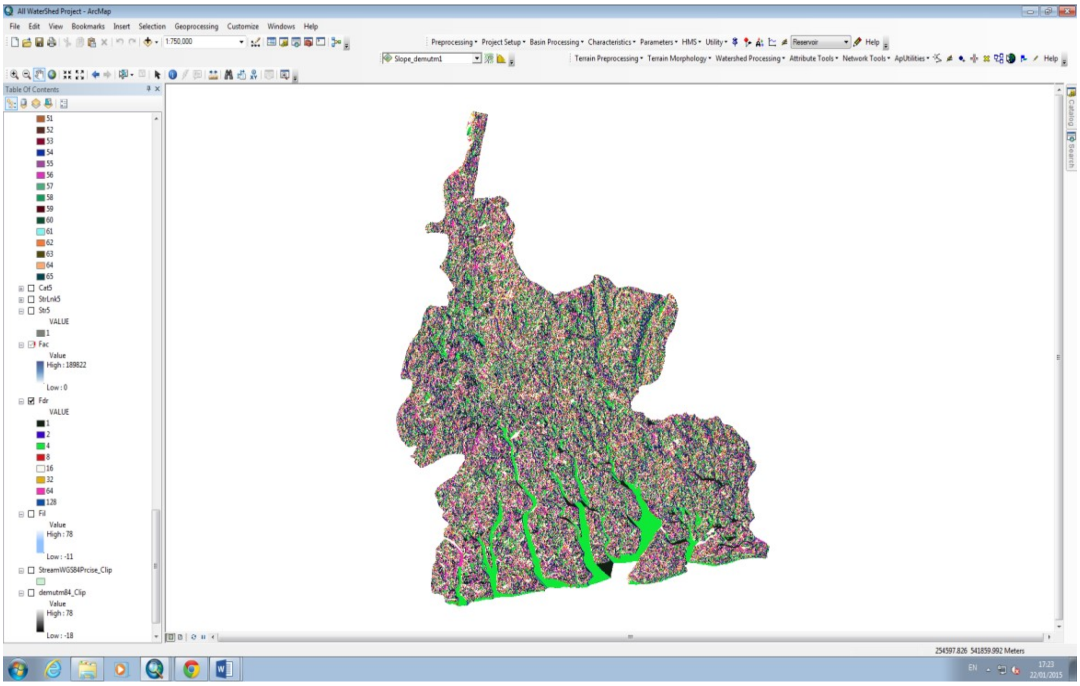


Figure 4.27 Map showing Flow direction in ArcMap.

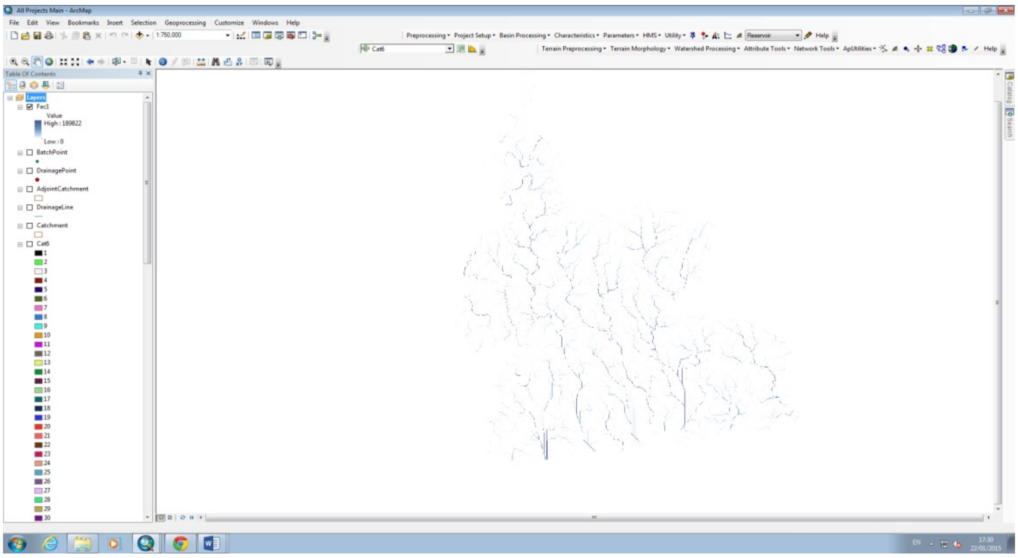


Figure 4.28 Map of flow accumulation delineated from DEM.

3. **Flow Accumulation (Fac) GRID**: This GRID is delineated from the flow direction GRID. It is defined by the contributing areas of the DEM (Figure 4.28). This function computed the number of upstream cells draining into any given cell in the input grid (Merwade, 2012a).

4. **Stream Definition (Str) GRID**: Next, stream cells which formed the stream network were demarcated based on a threshold number of cells that drain into each given cell. Smaller thresholds resulted in a denser stream network accompanied by a greater number of catchments (Merwade, 2012b). For the Greater Port-Harcourt watershed, the threshold for the definition of streams was set of 20.000 cells and 0.74 km^2. The output was a raster map with an interconnected network of grid cells that represented the stream network (Figure 4.29).

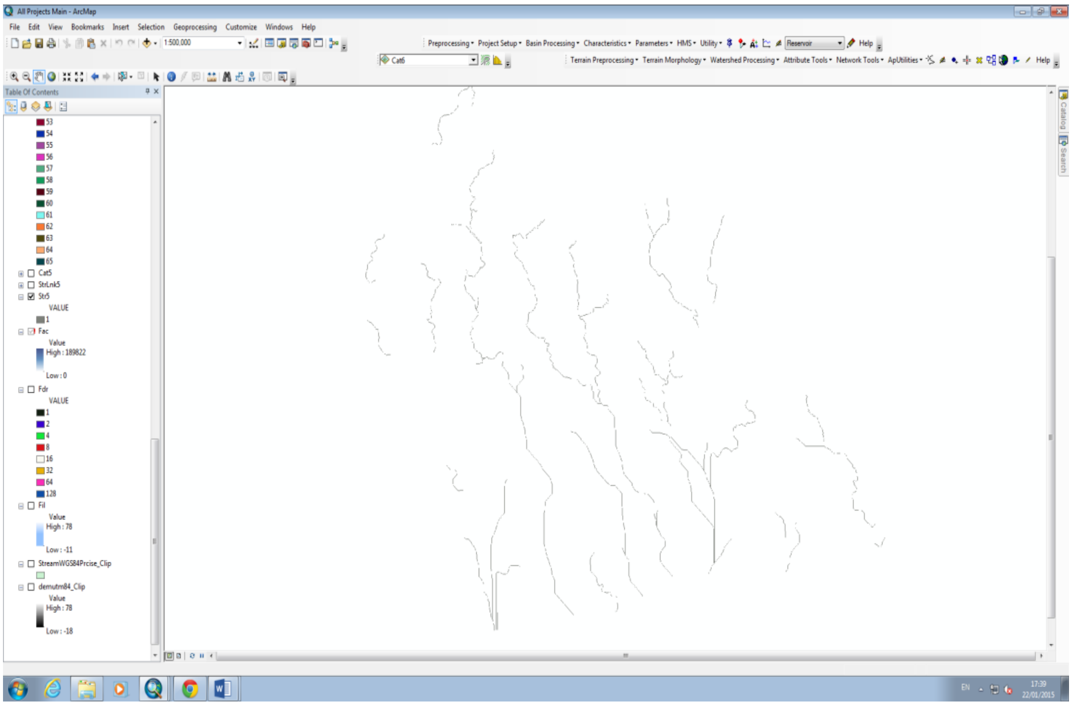


Figure 4.29 Map showing stream definition mapped during model pre-processing.

5. **Stream Segmentation (*StrLnk* GRID)**: Using the *Str* GRID and *Fdr* GRID as inputs, the stream segmentation task was performed. This function created stream segments with unique identification. The software identified head segments or segments between junctions. Hence, all cells in a given segment had the same grid code for that segment. The output was the Stream link Grid (Figure 4.30).

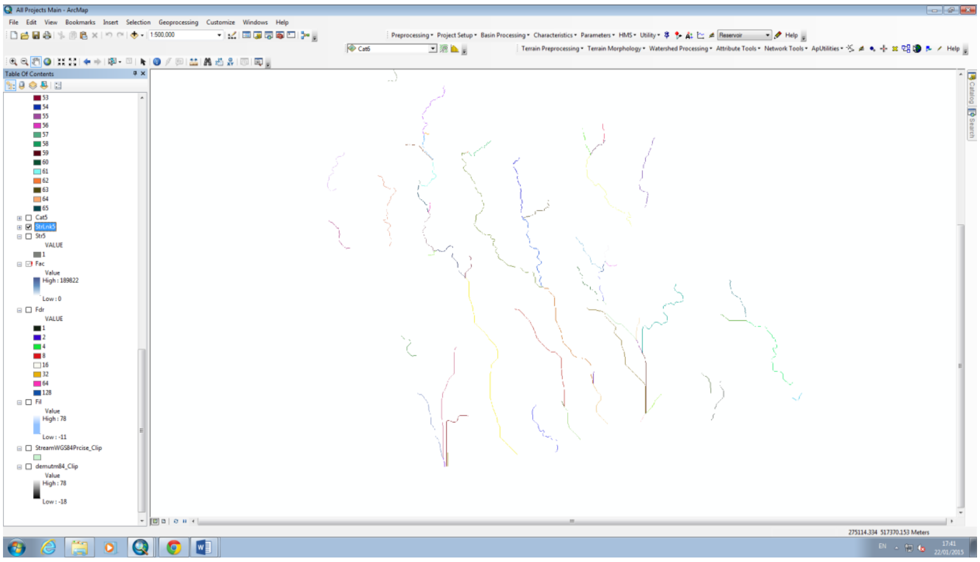


Figure 4.30 Map showing the stream segmentation during pre-processing.

6. **<u>Catchment (*Cat* GRID)</u>:** This was an important computation step where every stream segment carrying grid codes of a particular stream segment was used to delineate catchment that drain the area. Inputs where *Fdr* and *Str Lnk* GRIDS. Upon successful completion, the output was the Catchment or *Cat* GRID which was added to the map (Figure 4.31). Upon successful completion, subbasins were delineated.

7. **<u>Catchment Polygon Processing</u>:** At this stage, the input raster was converted to GIS vector format and stored in layers. This function converted the Cat GRID into catchment polygon feature and stored as a layer within in the geodata base associated with the map document (Figure 4.32). The input GRID was Cat and output was Catchment polygon feature *Catchment.* Upon completion of this process, the polygon feature class was added to the map. Within the attribute table, each catchment was automatically assigned a Hydro ID. The Hydro ID assigned was a unique identifier of each catchment. Importantly, the length and the catchment area were also computed and stored in the GIS environment for each catchment (Merwade, 2012b).

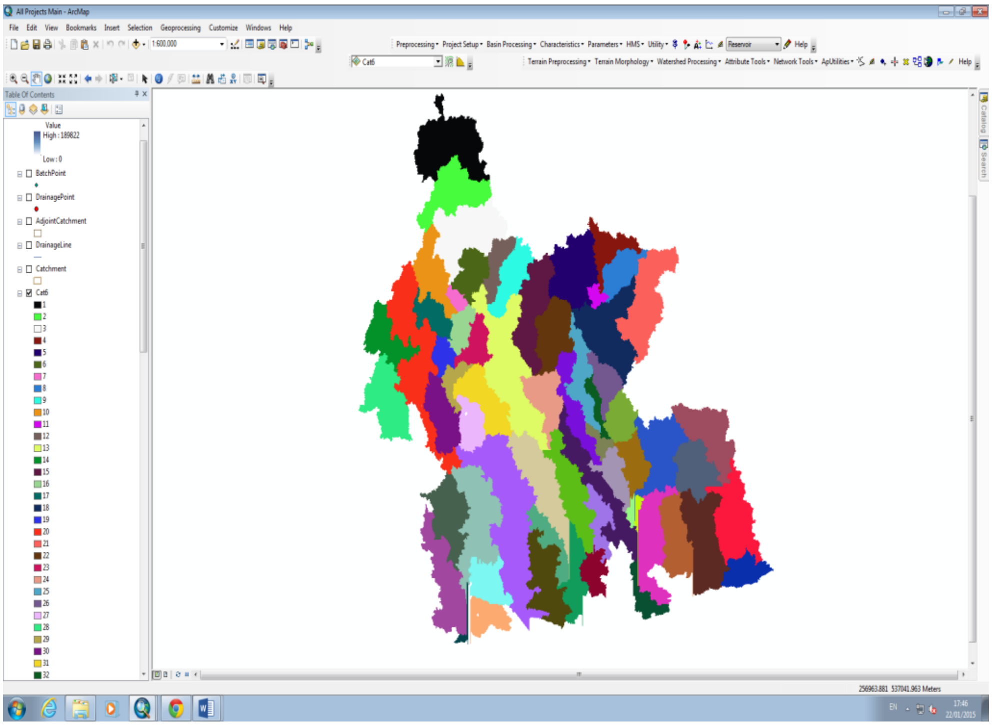


Figure 4.31 Catchments delineated for the entire study area during model pre-processing.

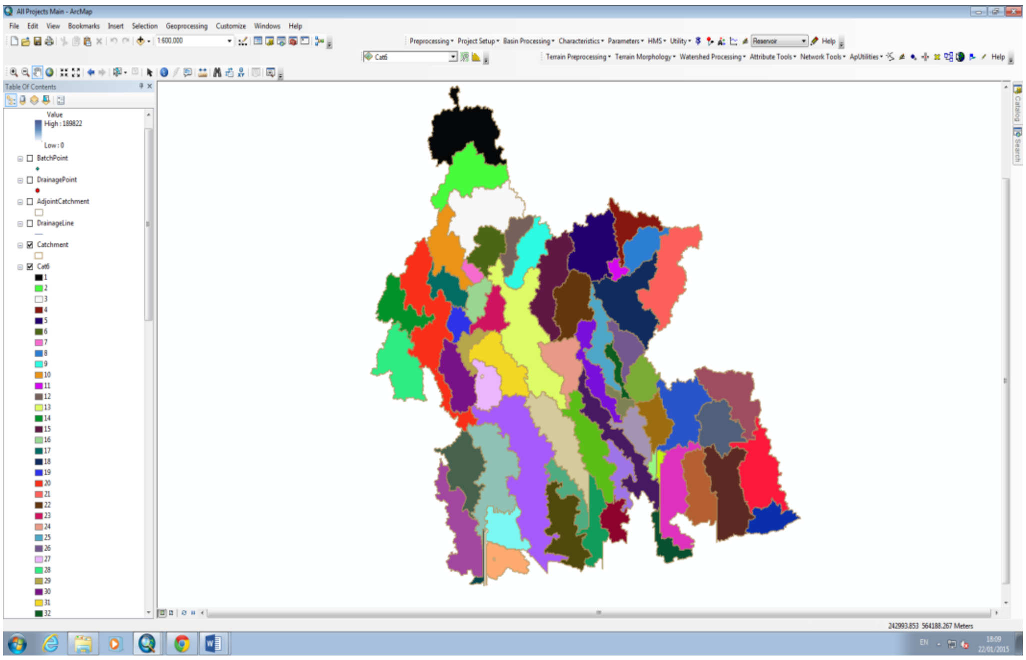


Figure 4.32 Map of Catchment in Polygon format.

7. **<u>Drainage Line Processing:</u>** This function also converted the already defined Str Lnk into a drainage line feature class. This essentially delineated the river or drainage

channels of the watershed. The input to this function was *Str Lnk* and *Fdr* GRIDS and output, the drainage line feature added to the map (Figure 4.33).

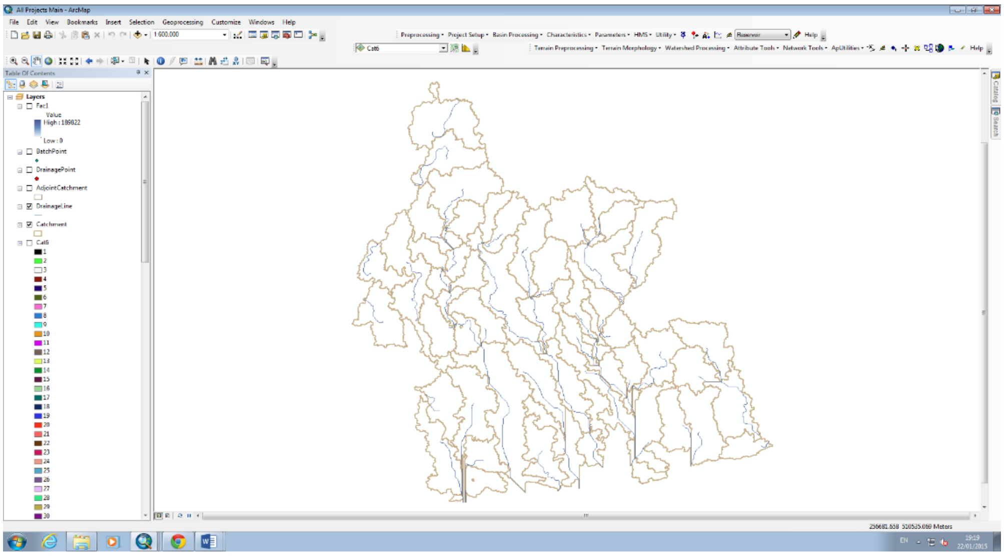


Figure 4.33 Map of Catchments with drainage lines.

8. **Adjoint Catchment Processing:** This function created the aggregated upstream catchments. For a given catchment that is not a head catchment, all polygon in upstream areas draining into its inlet were defined and stored as feature class that has an adjoint catchment tag. The inputs were drainage line and catchment respectively. Upon successful completion, a summary of the number of catchments aggregated was given (Merwade, 2012b).
9. **<u>Drainage Point Processing</u>**: This was the last step of the terrain processing phase. The function allowed for the generation of drainage points associated with the catchments. Inputs were the flow accumulation (*fac)* grid, catchment (*Cat)* grid and catchment polygon (Merwade, 2012b), while the output was drainage point.

B. Watershed Processing.

Based on datasets derived during terrain processing, this stage involved the use of Arc Hydro for delineating watersheds and sub-watersheds.

1. **Batch Watershed Delineation**: At this stage a batch watershed delineation task was performed to locate the outlet of a watershed (Figure 4.36). Watershed upstream were delineated based on batch points (Merwade, 2012b).

C. Basin Processing

Next, basin processing was done to further divide basins, and merge streams.

1. **Merge Basins**: Here two adjacent and very small basins were merged into one, taking the number of sub-basin from 39 to 37 (Figure 4.35).
2. **River Profile**: Afterwards, the River Profile tool was used for displaying and assessing the profile of selected river reach.

D. Basin Extraction

This stage involved extraction of the physical characteristics of streams and sub-basins into an attribute table (USACE, 2009; Merwade, 2012a), see Table 4.8. It included the topographic characteristics of the streams and sub-basins that were used for parameter estimation. The streams and sub-basin physical characteristics below were also stored in the attribute table, such as:

1. **River Length:** The first step involved the computation of river length selected for all the reaches and stored as *River Len.*
2. **River Slope:** Next, the slope of the river segment was computed by extracting the upstream and downstream elevation of the river reach. Afterward, the computed river slope was stored in the attribute table as *Slp.*
3. **Basin Slope:** By averaging slope values from slope grids of the sub-basin, basin slopes were computed. After computation, *BasinSlope* layer values were populated in the attribute table. Note this information is essential for computing CN lag.
4. **Longest Flow Path:** This tool was used to populate the longest Flowpath feature class. A polyline feature was stored which was later used for estimating the Time of concentration (T_c) parameter.

Table 4.8 The Basin's Physical Characteristics and Attribute table headings (USACE, 2009).

Data Layer	Physical Characteristics	Attribute Table Heading
Stream layer	Length	RivLen
	Upstream elevation	ElevUP
	Downstream elevation	ElveDS
	Slope	Slp
Sub-basin Layer	Area	Area
Sub-basin Layer	Centroid Location	
	Centroid Elevation	Elevation
Longest flow Path Layer	Location of longest flow path	
	Longest flow path	LongestFL
	Upstream elevation	ElevUS
	Downstream elevation	ElevDS
	Slope between endpoints	Slp
Centroid Flow Path Layer	Location of the centroid flow path	
	Centroid Length	CentroidFL

5. **Basin Centroid:** This tool computed the basin centroid which is the CenterPoint of each basin. This can be computed in 4 ways. Here the longest flow path method was used to compute the centroid as the midpoint of the longest flow path in the subbasin (USACE, 2009).
6. **Basin Centroid Elevation:** This tool was used to compute centroid point elevation using the DEM. The elevation was stored in the centroid layer attribute table.

7. **Centroidal Longest Flow Path:** This function computes the centroidal flow path by projecting the centroid to the longest flow path (Figure 4.34). It was automatically stored as *Centroidal* in the attribute table.

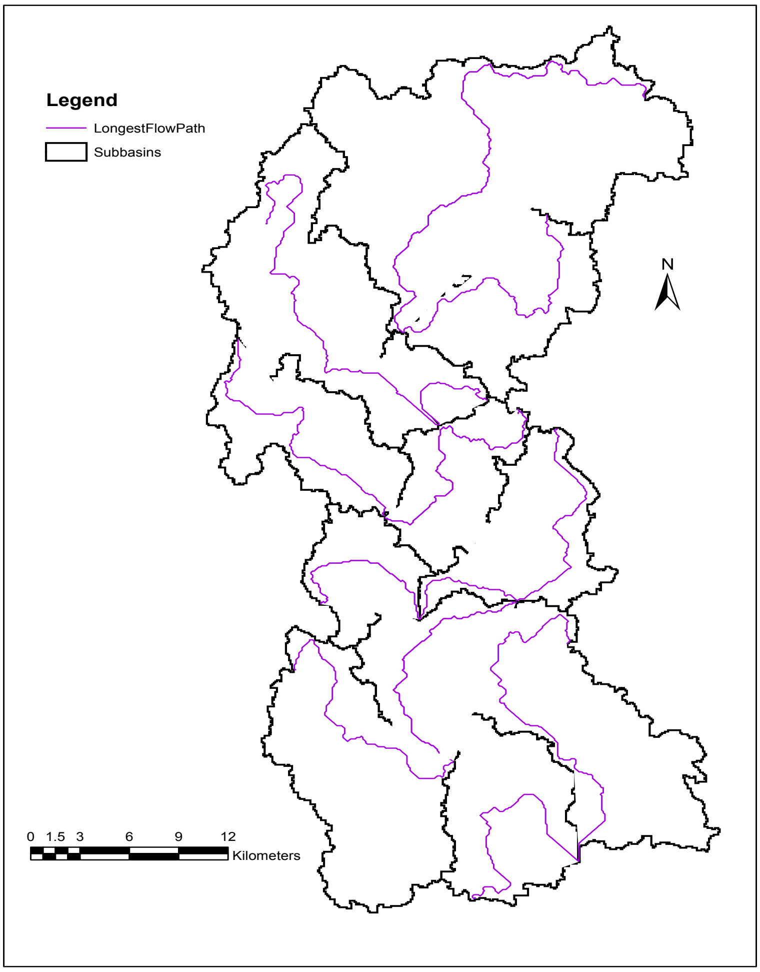


Figure 4.34 Map showing longest flow paths within sub-basins in the Degema basin.

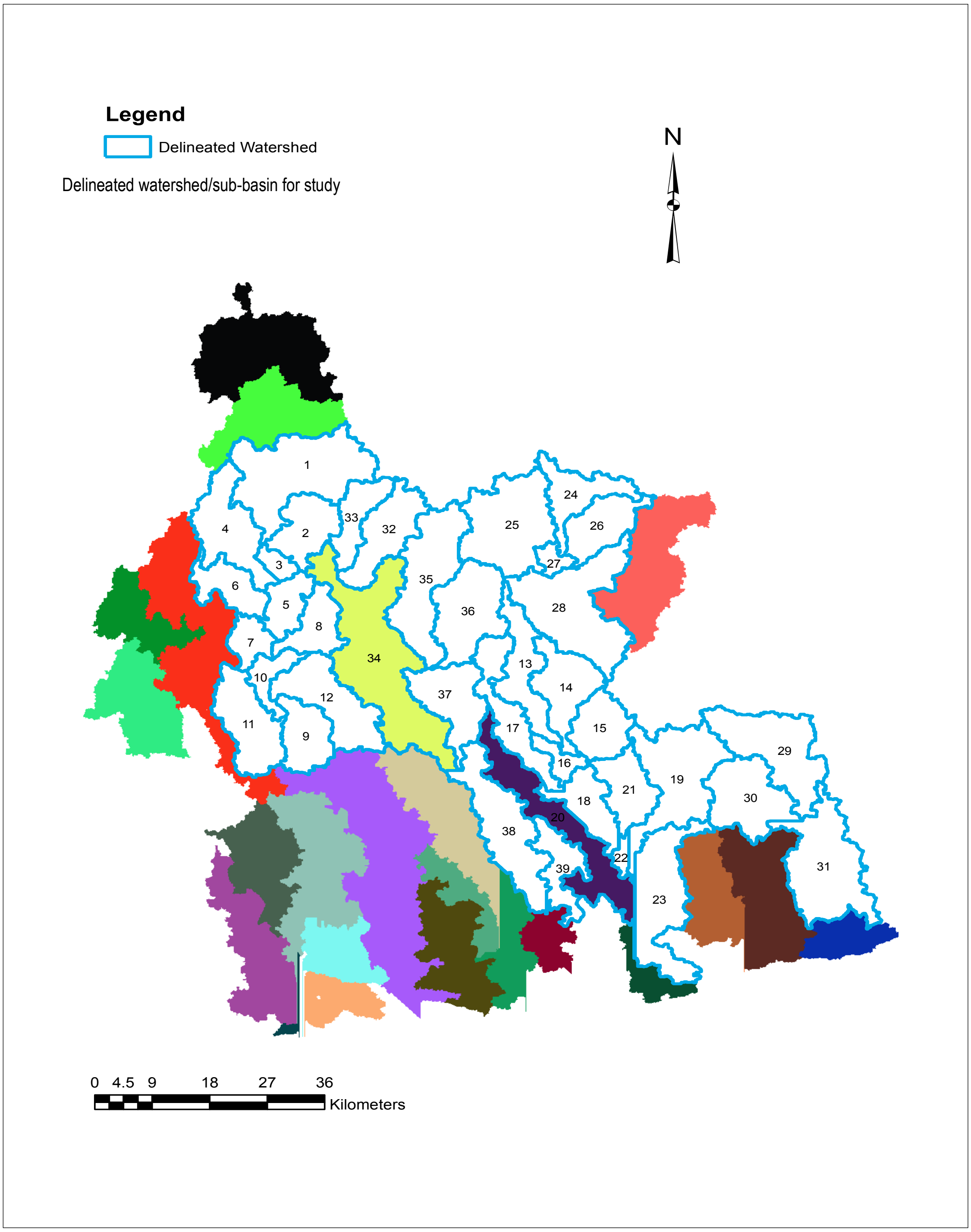


Figure 4.35 Map showing 39 GPH sub-basins delineated in HEC-GeoHMS.

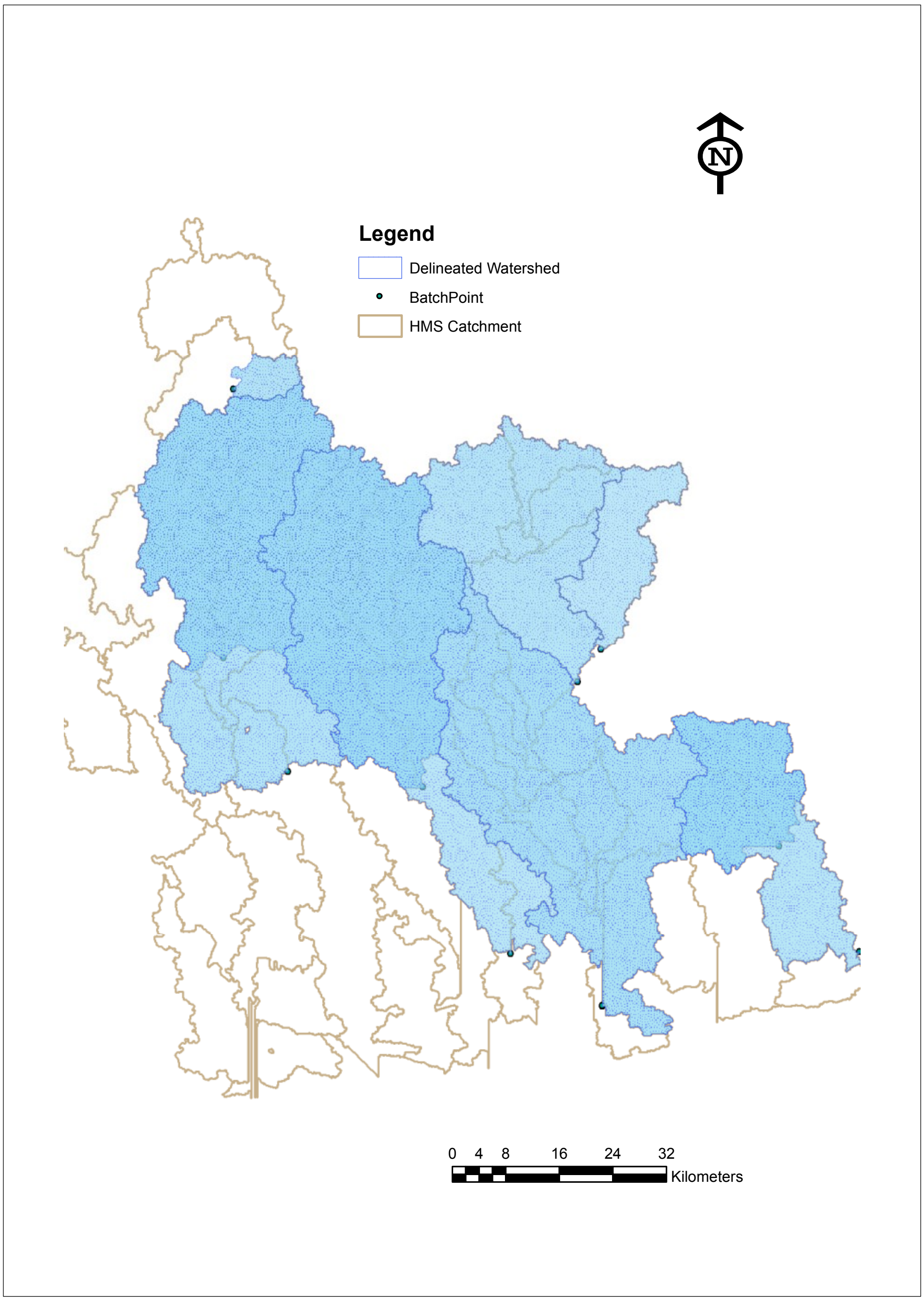


Figure 4.36 Map showing delineated basins within the entire study area.

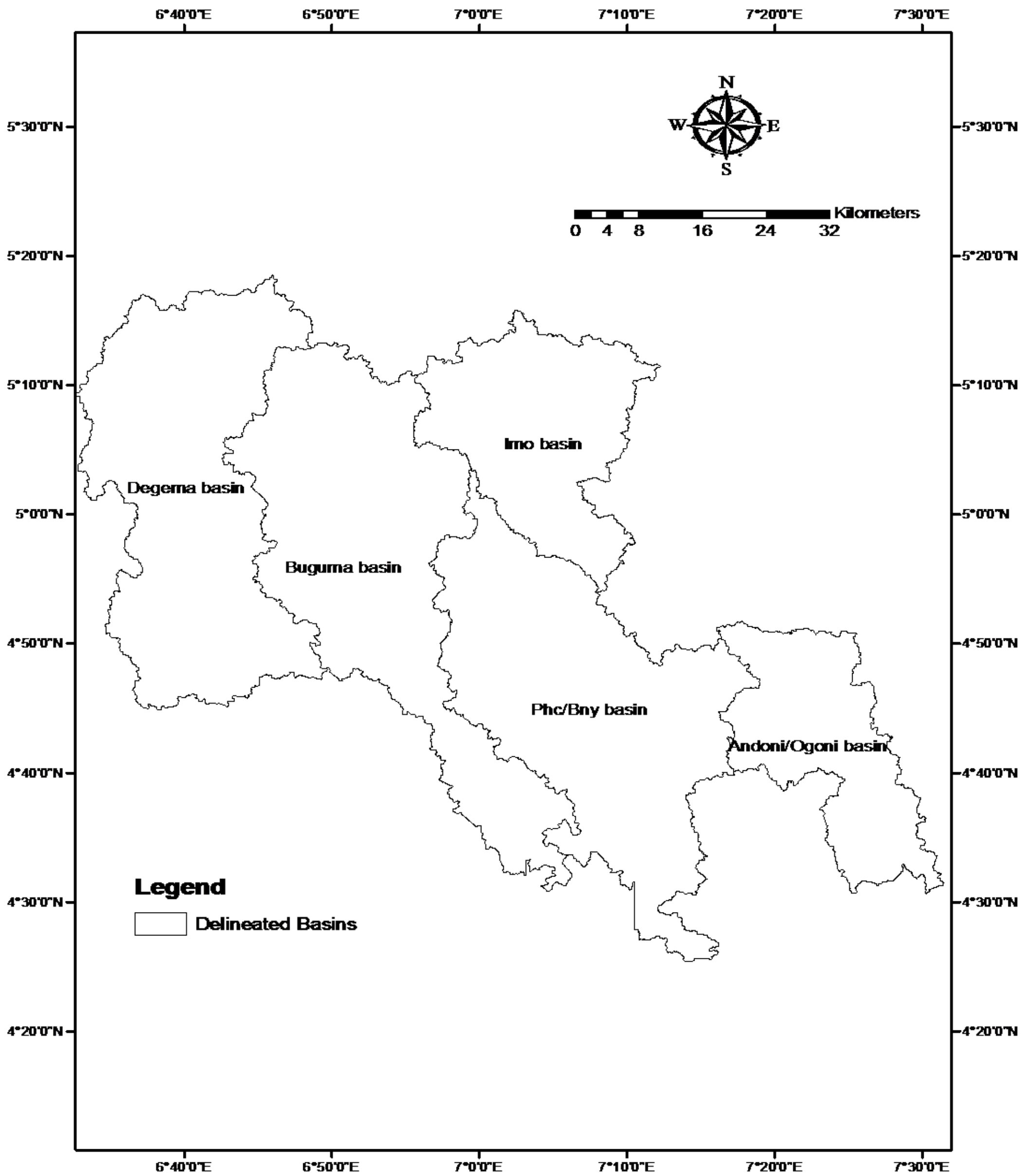


Figure 4.37 Map showing the location of the actual project area within the overall study area.

Figure 4.35 map shows a coverage of the actual project area (watershed) delineated for study area covering 39 out of the initial 56 sub-basins (catchment) delineated. Note: the number of subbasins was reduced to 37 because 2 very small sub-basins were merged into two large one. The watershed was delineated at the watershed processing and HMS project stage. To create the watershed of interest, outlet points downstream of a group of interconnected basins surrounding the GPH city area were selected. The respective project areas (basins) which made up the watershed were based on the 5 major outlet points (batch points). Five (5) basins surrounding the city were finally selected. Each basin (project area) generated represented the drainage area upstream of an outlet. As shown in Figure 4.36 and 4.37, five (5) of the basins delineated were aggregated to form the GPH watershed for study. These basins were selected because they were the major drainage area covering and surrounding the GPH city that were delineated by the HMS model. The five main basins include: Imo River Basin, Andoni-Ogoni Basin, Port-Harcourt-Bonny Basin, Bugema-Ikwere Basin and Degema Basin.

4.9.8 Model Application.

After terrain processing, parameter estimation `and pre-processing process, the HEC HMS 4.0 model was applied to compute flow. The software contains, the Basin Model, the Precipitation Model and the Control Model (USACE, 2013).

Basin Model.

First, the Basin Model was used to represent and construct the physical watershed, for example see Figure 4.34. Here hydrologic elements such as subbasins, reaches, outlets, junctions were added from HEC-GeoHMS and connected to model the real world. Imported hydrologic data, including maps were used to create a basin map.. Note, the imported files contained estimated parameters such as CN, PctImp, basin attributes, and elevation data that were managed in basin model. Next, the appropriate runoff-runoff-routing models described earlier were selected in the loss, runoff and reach components for simulation. Again, they are comprised of the:

1. Loss model-SCS-CN model
2. Transform model-SCS UH model
3. Routing-Muskingum-Cunge model

Figure 4.34 is an example showing basin map and other hydrologic elements constructed in HEC-HMS for Port-Harcourt/Bonny Basin in this study. The same was done for all five basins.

The Meteorological Model.

The Meteorological model component was used to model rainfall. In this study, the hyetograph method was used. The gauge option was used for running the historical events while the total depth option was used run the statistically derived and projected data. Note: the unit hydrograph method assumes uniform rainfall over all basins. For the historical event, the daily rainfall values and the total rainfall depth obtained from NIMET was inputted as shown in Table 4.9. The years of historical events selected corresponded to the year of land-cover acquisition. The average intensities of the maximum 24hr rainfall were also determined. For the future and design rainfall, a single value, i.e. the total rainfall depth of 183.7mm, 208.7mm and 290.09mm were entered for the A2 (44yr), A1B (57yr) projected storms and the100yr design storm respectively.

Table 4.9 Meteorological data used for modelling historical events.

Rainfall	1986	1995	2003	A2	A1B	T100
Duration	96hrs.	48hrs.	72hrs.	24hrs.	24hrs.	24hrs.
Number of storm days	4	2	2			
Duration	(2nd to 5th July)	(11th to 12th Oct)	(1st to 2nd Jul)			
Peak storm depth (mm)	104.3	126.7	173.4			
Daily rainfall (mm)	22.1, 104.3, 53.1, 30.6	5.2, 126.7	13.2,			
24hr AMDR average intensity (mm/hr.)	4.35	5.28	7.24			
Total storm Depth (mm)	210.1	131.9	186.6	183	208.7	290.1

Control Specification.

The Control specification component was used for regulating timing and is comprised of duration, start and end times as well time steps for the simulation. The duration of historical rainfall entered for 1986, 1995 and 2003 were 4, 2 and 2 days respectively. The respective dates are stated above in Table 4.9. The duration of the projected and design storm were 24hrs and a 10mins time step was applied in all model runs. Figure 4.38 captures the graphical user interface of the model during the model run.

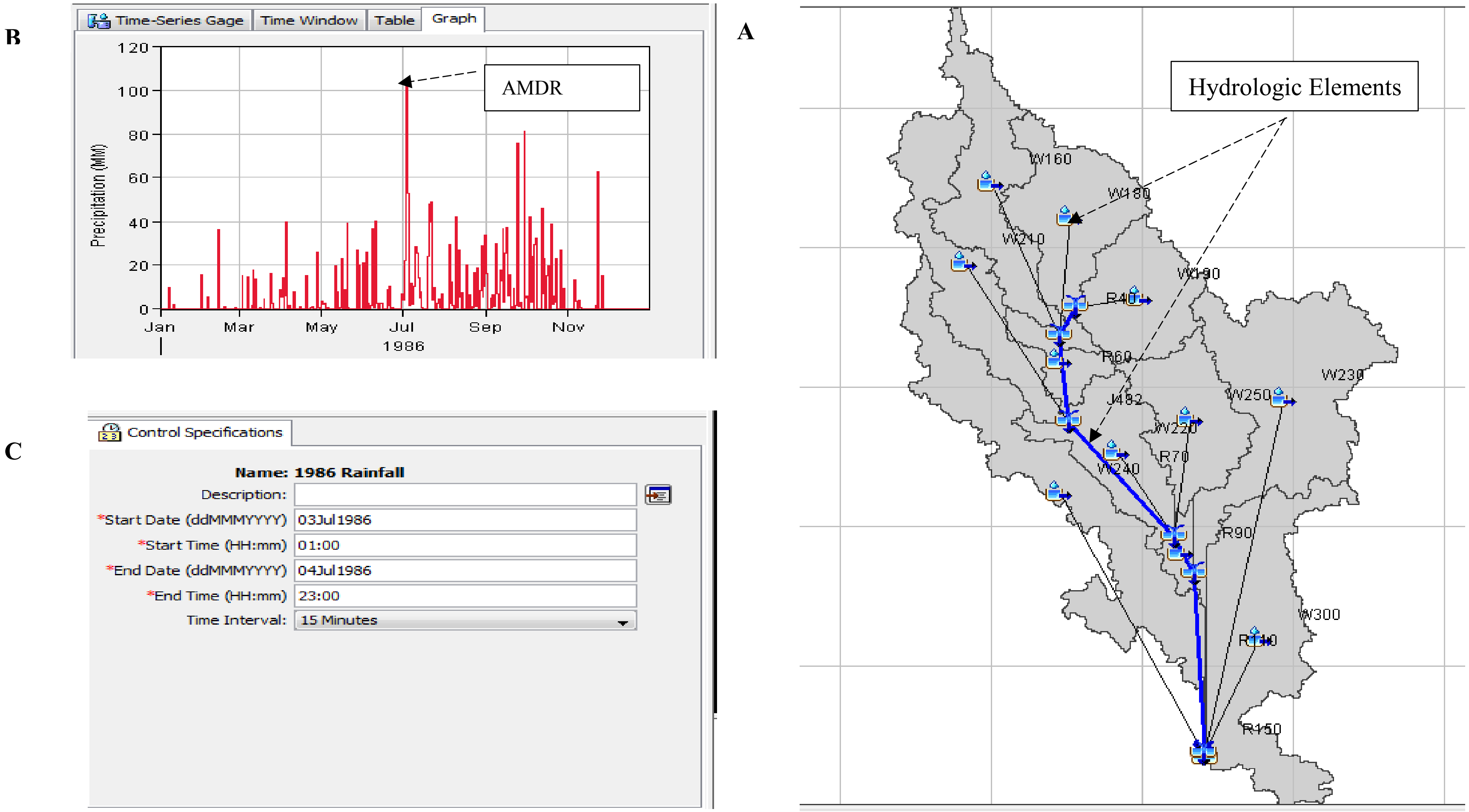


Figure 4.38 An example of HMS Model components constructed for the Port-Harcourt-Bonny basin (1986) showing: A-Basin model; B-Meteorological model; and C- Trial control specification.

4.9.9 Calibration and Validation.

Calibration.

In this study, sub-basins were ungauged which is a typical problem in most developing countries, hence, calibration was not possible due to the unavailability of adequate observed discharge data. To overcome this problem, an alternative method known as the prediction in ungagged basin (PUB) method was adopted as seen in Ford et al. (2002); Roy and Mistri (2013). Model parameters for loss, transform and channel routing was mainly derived from the digital elevation model (DEM), soil and satellite land cover maps. PUB approach uses characteristic of the watershed. These are the physical, measurable properties of the watershed such as area, slope, roughness coefficient, channel slope, channel bottom width, reach length, etc. (Lange and Leibundgut, 1999; Ford et al., 2002). Several studies have used this approach, for example, see Kokkonen et al. (2003); El-Hames (2012) and (Ford et al., 2002). Loss-initial abstraction parameters were estimated in HEC-HMS using NRSC-CN values. Transform-lag parameter was also estimated using longest flow path and distance to basin centroid derived from DEM. In addition, the channel routing was possible by means of the Muskingum-counge method where geometric data such as: channel length, slope, channel shape, side slope, and channel width as well as roughness coefficient (Manning's N) were used. See Table 4.10 for geometric data measurements. However, experience from existing studies show that PUB methods and physically-based theoretical models provides reasonable estimates of model parameters (Lange and Leibundgut, 1999; Ford et al., 2002; El-Hames, 2012; Roy and Mistri, 2013)

Table 4.10 Channel Geometry Data derived for Flood Routing.

Reaches	Length (m)	Slope	Manning	Shape	Side Slope	Width (m)
AO						
R30	28037	0.2198	0.05	Triangle	0.0522	
IMO						
R40	5959.6	0.508	0.05	Triangle	0.0317	
R50	29566	0.4496	0.05	Triangle	0.043	
PHC/BNY						
R40	3620.7	0.0022	0.05	Triangle	0.667	
R60	8782.2	0.0255	0.05	Triangle	0.0185	
R70	14350	0.22	0.05	Rectangle		365.71
R90	3888.9	0.041	0.05	Rectangle		1691.84

Reaches	Length (m)	Slope	Manning	Shape	Side Slope	Width (m)
R110	16016	0.055	0.05	Rectangle		6114.18
R150	130.82	0.002	0.05	Rectangle		3017.27
R130	65.409	0.69	0.05	Rectangle		3017.27
BUGUMA						
R50	55893	0.005	0.05	Triangle	0.0304	
R60	23343	0.017228	0.05	Triangle	0.042	
R70	46.251	0.000025	0.05	Rectangle		364.46
R80	32259	0.000025	0.05	Trapezoid	0.024	90.6
DEGEMA						
R40	8046.1	0.0022	0.32	Triangle	0.23	
R60	11313	0.225	0.32	Triangle	0.0077	
R70	9072.9	0.22	0.05	Triangle	0.042	
R90	13852	0.041	0.05	Triangle	0.086	
R110	65.409	0.055	0.05	Rectangle		549.66
R120	15055	0.69	0.05	Rectangle		915

Validation.

Model validation is the final and important level of any model analysis that deals with uncertainty and accuracy. In this study, validation of the HEC-HMS model was performed for four year time periods (1985, 1987, 1988 and 1989 respectively). These time periods selected for validation were different from the time period used in the model run and are based on time periods for which observed peak discharge data were available. Observed peak discharge data for Imo River Basin Data was found in the recent published work of Okoro and Uzoukwu (2013) spanning 1985 to 1998. This was used for validation in the absence of adequate data. In this study, it was assumed that good model performance for the Imo River basin will also yield a good performance for the other four (4) basins.

Three validation criteria were used to analyse performance, including: mean absolute error (MAE), relative percentage error (RPE) and root mean squared error (RMSE) (Equations. 4.16-4.18). The MAE measures the average magnitude of the errors in a dataset of forecasts, ignoring their direction while, the RMSE is a quadratic scoring equation that measures the average magnitude of error (Chai and Draxler, 2014).

$$\text{MAE} = \frac{\sum_{i=1}^{N} |Qop_i - Qep_i|}{N}$$ ***Equation 4.16***

$$\text{RMSE}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}|Qop_{i-}\ Qep_i|^2}$$ ***Equation 4.17***

$$\text{RPE}=\frac{1}{N}\sum_{i=1}^{N}\left|\frac{Qop_{i-}\ Qep_i}{Qop_i}\right| * 100$$ ***Equation 4.18***

Where = Q_{op} = Observed peak discharge; Q_{ep}= Estimated peak discharge. N= number or samples

4.9.10 FLOOD INNUNDATION ANALYSIS USING Hydraulic modelling TECHNIQUE.

This section justifies the methods and describes the process of hydraulic modelling and mapping used for analysing flood hazard in this study. The modelling process was based on procedures described in the HEC-GeoRAS and HEC-RAS manual for calculating water surface elevation. This section is primarily structured into model description, preprocessing and model application. Figure 4.39 is a flow chart showing the work flow.

Hydraulic modelling/mapping.

Hydrologic flood models are mainly used to estimate flood flows, meanwhile hydraulic flood modelling and mapping are used for estimating and visualising changes in flood depth, extent and velocity (Tate and Maidment, 1999; Knebl *et al.*, 2005; Moradkhani *et al.*, 2010; Iqbal and Khan, 2014). Hydraulic modelling allows the accurate estimation of changes in flood hazard parameters such as flood depth, flood extents and velocities for rivers and watercourses (Chanson, 2004; Akan, 2006). Hydraulic models are used to estimate free surface flow dynamics by means of physical and mathematical models. The benefits of flood mapping are clear. People, flora, fauna and properties in the Port-Harcourt are exposed to flood extremes that lead to substantial loss of life (GFDRR, 2013). Hydraulic modelling and mapping aid in providing flood risk related information for decision-making. They are generally used for a variety of human and environmental intervention strategies, including: river management, flood risk management strategies, land-use planning and management, emergency and disaster planning, insurance and raising of public awareness. In this study, flood modelling and hazard mapping were used to understand the effects of land-use and climate change on flood depth, extent and velocity. In this study, it was used to address the question: *What are the effects of land-use changes and climate change on flooding in the GPH watershed?*

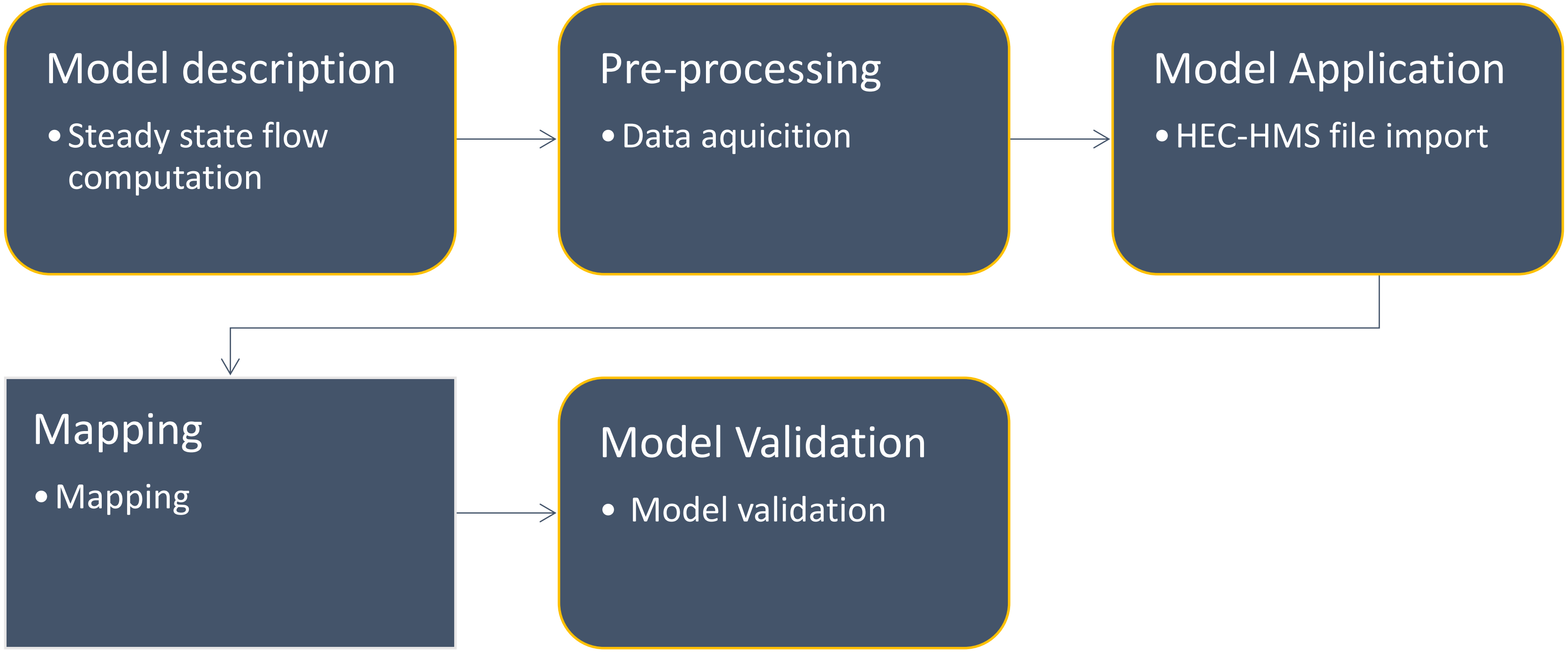


Figure 4.39 Flow chart showing the hydraulic modelling work flow. The HEC-RAS modelling process involves Model description, Pre-processing, Model application, Mapping and Model validation.

Flood hazard analysis and mapping methods.

Flood hazard analysis/mapping can primarily be carried out in two ways which can be grouped into: geological-geomorphological methods and hydrological-hydraulic methods (Lastra *et al.*, 2008; Duan *et al.*, 2009; Kalantari *et al.*, 2014). The first group uses historical aerial photograph, geological data and field survey to determine bank over flow. (Kourgialas and Karatzas, 2011). It is based on the principle that the outer limits of a stream's flood plain constitute the outer envelope of past floods (Ballais *et al.*, 2005). Whereas, the hydrologic-hydraulic methods rely on historic hydrologic data for simulating water surface elevation (WSE) and surface extent. Geomorphological mapping uses geological techniques for observation of floodplain by means of paleo channels, erosive marks, crevasses as well as old and recent over bank. Although the geomorphological methods are considered reliable, easy to use and inexpensive (Ballais *et al.*, 2005; Lastra *et al.*, 2008). The hydraulic method was used for flood hazard analysis in this study because it can be used to understand the historical floods and future changes in floods depth, extent and velocity.

Hydraulic Models.

To date, a number of hydraulic models exist that can be classed as 1-D, 2-D and 3-D hydraulic models. Hence, several key studies have applied these models to accurately predict flood depth, extent and velocity and their distribution (Bates and De Roo, 2000; Horritt and Bates, 2002; Tahmasbinejad *et al.*, 2012; Mohammadi *et al.*, 2014). In general, the models rely on peak flow data in addition to terrain and geometric data for the construction of water surface extent (WSE), flood depth and flood velocity (Bates and De Roo, 2000). While there is a huge debate on the best choice for delineating flood inundation extent in studies, 1-D models are frequently used for dealing with inundation problems (Bates and De Roo, 2000).

1-D hydraulic models are solved by one-dimensional finite difference (St. Venant's equations) which have been used to develop models software, including: ONDA, FLUCOMP, ISIS, HEC-RAS, MIKE11 (Bates and De Roo, 2000; Horritt and Bates, 2002; Hicks and Peacock, 2005; Yang *et al.*, 2006). These schemes simulate the flood plain and river channel as a series of cross sections perpendicular to the direction of flow (Bates and De Roo, 2000; Horritt and Bates, 2002), however hydraulic models generally demand a lot of data which remain a huge barrier for modelling in data sparse regions such as Nigeria (Sanyal *et al.*, 2014).

To address the research question, HEC's River Analysis System (HEC-RAS) software version 4.1 was used. HEC-RAS developed by the United States Army Corps of Engineers have been extensively used for solving river hydraulic problems (Knebl *et al.*, 2005; Fan *et al.*, 2009; Heimhuber, 2013; Mohammadi *et al.*, 2014). In this study, it was applied in performing one-dimensional steady state analysis for determining the water surface elevation (WSE) and flood extent and velocity. Prior to model run, HEC-GeoRAS extension in ArcMap environment was used to pre-process the geometric data, LULC data and elevation data inputs.

Rationale for selection.

The software was selected because: (1) it can be used to perform 1D steady and unsteady flow calculations for full network of natural open channels. (2) Moreover, it has been successfully applied in many previous studies which indicates the model can provide reliable estimates of WSE etc. For instance, HEC-RAS has been used for modelling WSE in: Neka River, Iran (Mohammadi *et al.*, 2014); Taipei area of Taiwan (Fan *et al.*, 2009); Oregon, USA (Tripathi *et al.*, 2014). (3) Unlike raster based models e.g. LISFLOOD-FP, HEC-RAS can be calibrated against discharge or inundated area data of another event in the same reach and provide acceptable results, but LISFLOOD-FP requires calibration against an independent inundated area data to produce acceptable results (Horritt and Bates, 2002). (4) HEC-RAS is classed as a 1D model, based on the amount of computational resources used by the algorithms, HECRAS 1D model is considered computationally more efficient than 2D and 3D inundation models. (Hunter *et al.*, 2007). Finally, HEC-RAS is considered a reliable model by experts and can be found in the public domain (Horritt and Bates, 2002; Hicks and Peacock, 2005).

4.9.11 HEC-RAS Model Description.

The HEC-RAS model is capable of performing 1D gradually steady, varied flow computation for a network of rivers or man-made open channels (Rodriguez *et al.*, 2008; USACE, 2010; Van, 2010). The model developed by the USACE was designed with variety of applications and is often applied for inundation modelling, flood forecasting, flood plain management, flood-way encroachment analysis (USACE, 2010). Since 1964, there has been changes from version such as HEC-2 to HEC-RAS. HEC-2 was a standard stream hydraulic analysis program capable of modelling bridge, weir, and culvert analyses among other things. HEC-RAS was used because it is capable of modelling movable boundary sediment transport calculations and unsteady state flows among other things (USACE, 2010). Importantly, it was used because it is also capable of calculating supercritical, mixed and subcritical flow regimes for river channels. Generally, the main input parameters required by the model are channel geometry and the flow data. Other important input parameters include: network connectivity, hydraulic structures, contraction-expansion coefficient, stream junction data and roughness coefficients (Manning's N).

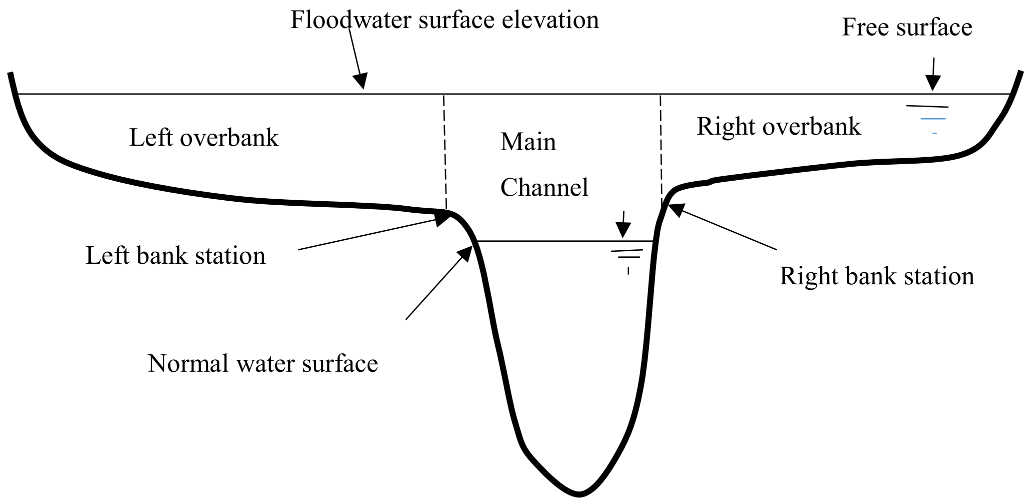


Figure 4.40 Schematic diagram of the stream cross-section of an open flow channel.

Theoretically, open channel flow is used to explain the movement and depth of water through natural river channels. Open channels (Figure 4.40) have free surface and are subject to atmospheric pressure (Montes, 1998). In hydraulics studies, three basic principles consisting of conservation of mass, energy, and momentum are applied to solve problems of open-channel flow (Montes, 1998; Horritt and Bates, 2002; Chanson, 2004; Akan, 2006; Rodriguez *et al.*, 2008; Van, 2010; Mohammadi *et al.*, 2014). Based on these principles, three fundamental equations derived known as St Venant's equations are solved by models. They include the continuity equation, energy equation and the momentum equation (Montes, 1998; Chanson, 2004; Akan, 2006).

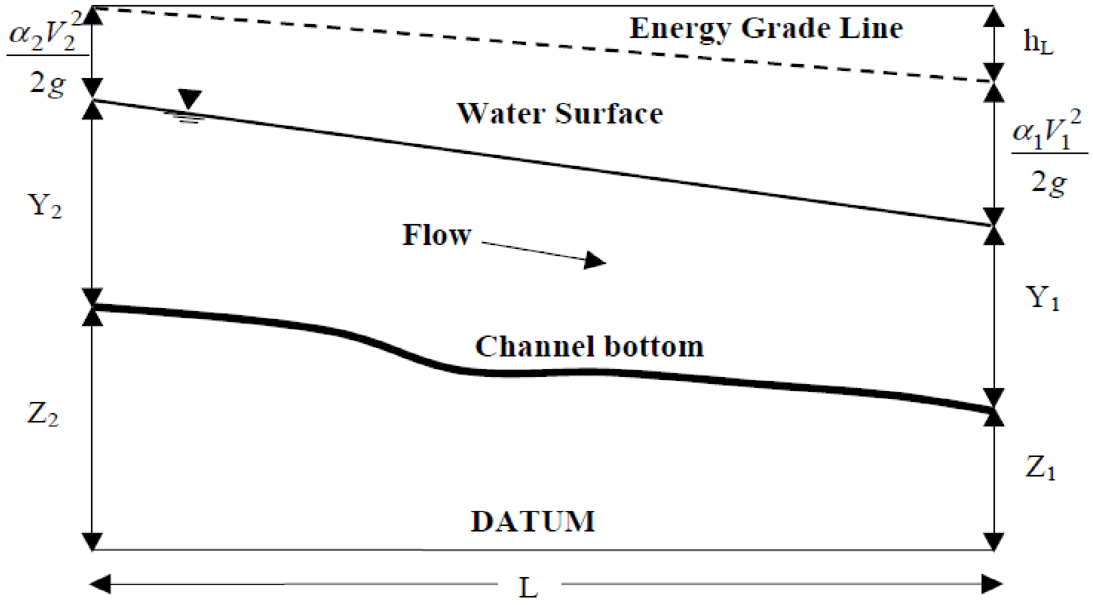


Figure 4.41 Representation of terms in the energy equation.

In HEC-RAS, steady gradually varied flow is calculated by solving the St. Venant's energy equation (Duan *et al.*, 2009; USACE, 2010). Steady flow means that a constant flow rate is assumed throughout an analysis. That is to say, the flow velocity does not change with respect to time at a given location. Again, flow is said to be steady if flow depth at different points do not change with time (Chow, 1959; Chaudhry, 2007). Figure 4.41 is a short length of channel used to represent terms in energy equation (USACE, 2010). From the diagram, three main components make up the total energy head per unit area, that is: elevation head, pressure head and velocity. Generally, gradually varied flow require the application of energy and frictional resistance equations.

The energy equation is expressed as

$$Z_2 + Y_2 + \frac{\alpha_2 {V_2}^2}{2g} = Z_1 + Y_1 + \frac{\alpha_2 {V_2}^2}{2g} + h_e$$ ***Equation 4.19***

Where: Z_1 Z_2 = elevation of the main channel inverts

Y_1 Y_2 = water depth at cross sections or pressure head

V_1 V_2 = average velocities (total discharge /total flow)

α_1 α_2 = Velocity weighting coefficient

h_e = energy head loss

Moreover, the energy head loss between two cross sections in a reach also consist of frictional losses and contraction or expansion losses expressed as:

$$he = LS_f + C\left|\frac{\alpha_2 {V_2}^2}{2g} - \frac{\alpha_1 {V_1}^2}{2g}\right|$$ ***Equation 4.20***

Where L= discharge weighted reach length

S_f=representative friction slope between two section

C=expansion or contraction loss coefficient

Conveyance explains the movement of water downhill from points of higher energy to points of lower energy until it reaches a point of equilibrium, such as an ocean. This is enabled by the presence of natural conveyance channels e.g., streams, and rivers (Akan, 2006). Conveyance for a cross section in HEC RAS is calculated from the Manning's equation given as:

$$K = \frac{1.486}{n} AR^{2/3}$$ ***Equation 4.21***

Where: K= conveyance for subdivision

N=Manning's roughness coefficient for subdivision

A=flow area for subdivision

R=hydraulic radius for subdivision (area/wetted perimeter)

Supercritical flow computations begin at the downstream boundary and proceed upstream. For subcritical flow, the computations begin at the upstream boundary and proceed downstream. In this study mixed flow regime was computed because of the objective of the study.

4.9.12 Model Application and Procedure.

The hydraulic modelling and mapping procedure in this study followed three basic steps, namely: pre-processing, and model run and post-processing (Figure 4.42). The pre-processing of geometric data for export was first carried out using HEC-GeoRAS in ArcMap environment.

Next, model run and hydraulic analysis was performed using HEC-RAS, while post-processing intended for visualisation was performed using HEC-GeoRAS. See subsection for detailed explanation.

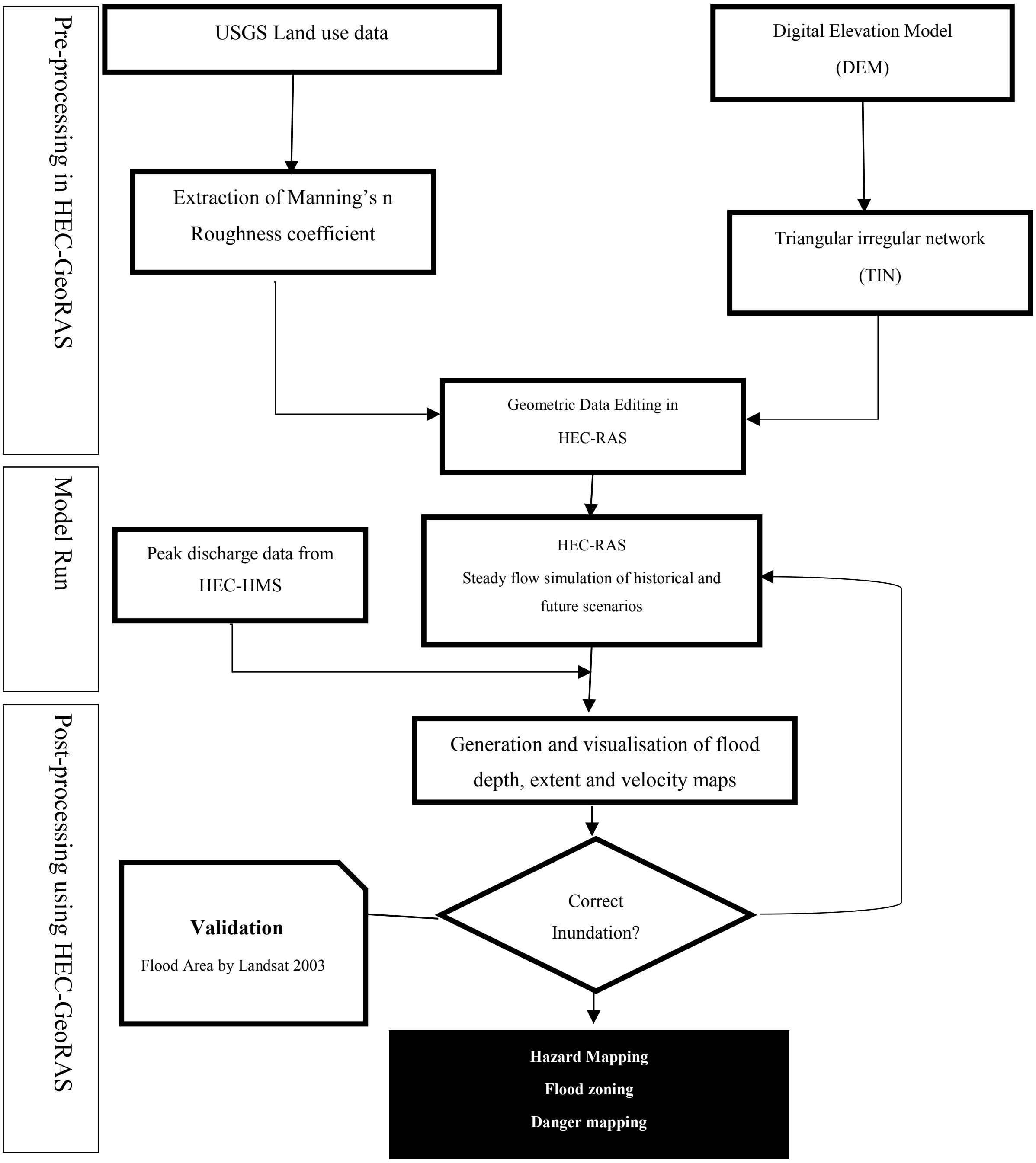


Figure 4.42 Simplified procedure for analysing 1-D flood plain in this study.

4.9.13 Data requirement.

First, in order to perform steady state flow computations of water surface elevation at all locations using HEC-RAS, some basic data were required. The data inputs can be grouped into 4 categories (Figure 4.43) including: Terrain data, Geometric data, Land use data and Steady flow data (see detailed explanation below). The input data extent depended on the type of data. The geometric data span the entire watershed 4821km^2, whereas the DEM and Manning's n data covered the entire study area that span about 10,400km^2 to allow for the construction of overbank areas outside the delineated watershed boundary. In other words, the width of some channels and overbank areas extend beyond the actual watershed area, for this reason a number of cross-sections and flow path lines were constructed outside the watershed boundary to properly construct the bank stations and over bank areas. And not all rivers were selected for modelling because of the very high drainage density. Selection of rivers was based on three factors, which were: size of channel, major channels within the area of interest and quality of river bed data.

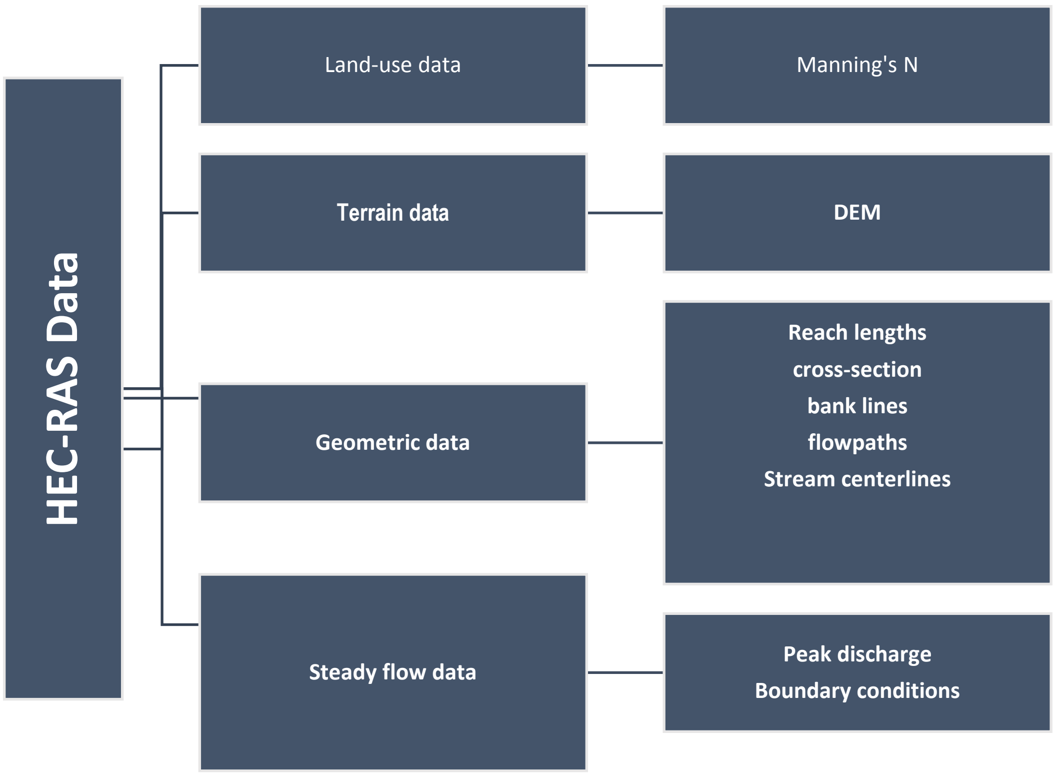


Figure 4.43 Types of Data used for Flood plain mapping in this Study.

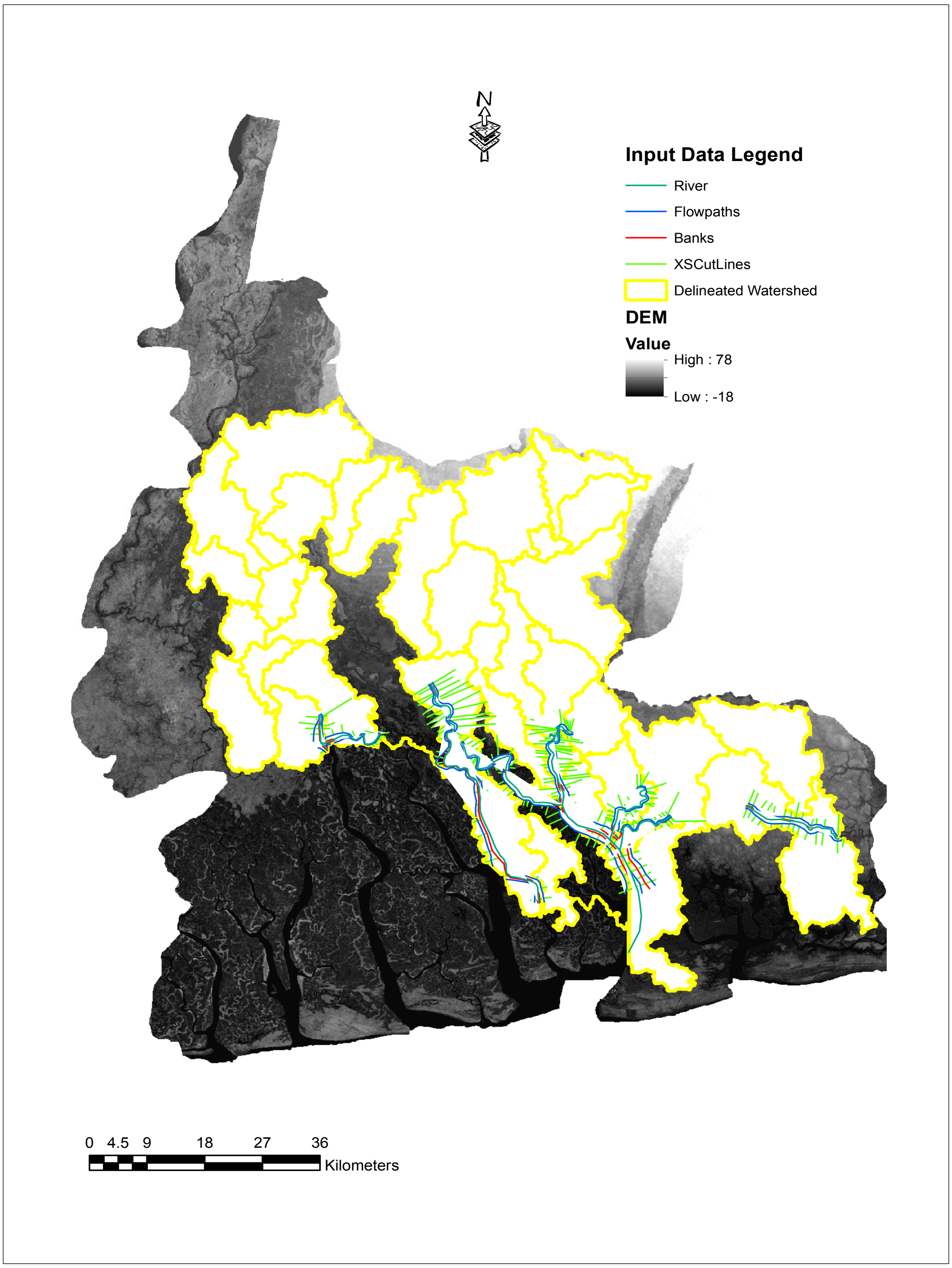


Figure 4.44 Example of Geometric and DEM data input used to define data extent.

The GPH watershed is comprised of a very dense network of rivers (Figure4.44) and only major rivers within the delineated watershed area were modelled. The readily available 90x90m DEM is coarse and produces less accurate vertical and horizontal representation of the channels than the 30 x 30m available in the United States (Keeratikasikorn and Trisirisatayawong, 2008).

Hence, many minor river channels upstream were not properly represented after TIN conversion and could not be used for modelling. Therefore major rivers within the watershed area with good river representation were selected to address the research objective.

Geometric Data.

The basic geometric data used in this study include: cross-section cutline, reach length, channel and bank lines, stream junction data, flow paths, stream centerlines and energy loss coefficients (i.e. frictional losses, contraction and expansion losses). Geometric data were required to establish connectivity of the river system (Ackerman, 2009; Brunner, 2010). The connectivity of the river system is also referred to as the river system schematic.

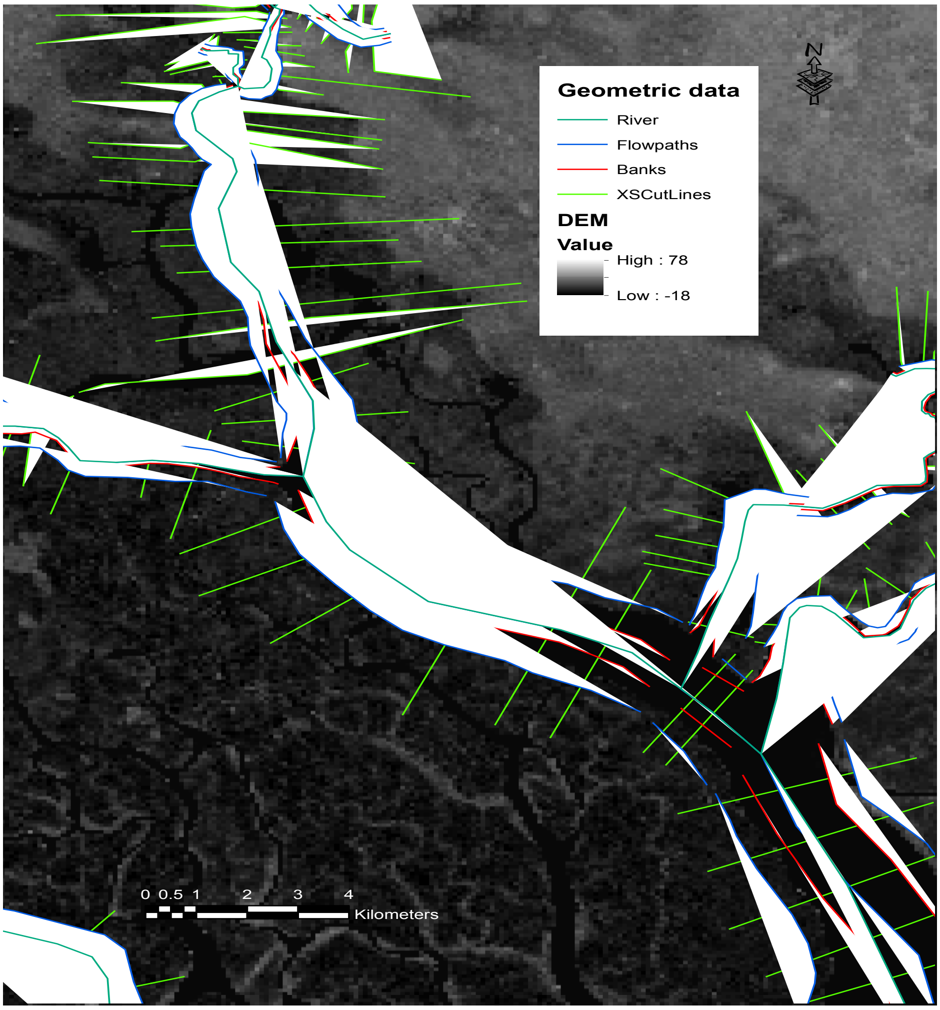


Figure 4.45 An example of geometrical data constructed for part the Greater Port-Harcourt watershed consisting of cross-section lines, flow paths, bank lines and rivers.

1. **Cross-section cutline**: Cross-section cut lines as shown in Figure 4.45 represent the spatial stationing (x and y coordinates) of cross sections (Ackerman *et al.*, 2000). This represents the ground surface profiles that were located at intervals. Cross sections stretch across the streams to both sides of the floodplain normal to the stream centerline. Although cross-sections can be constructed directly in HEC-RAS, in this study, they were created in HEC-GeoRAS and exported. Figure 4.45 shows an example of a cross-section layout in the Port-Harcourt area cutting across streams, flow paths and bank lines all overlain on the DEM (USACE, 2010).
2. **Reach Lengths**: Reach lengths were entered for all rivers
3. **Main channel bank lines**. The main channel bank lines define the station location and were constructed using the editor tool in HEC-GeoRAS
4. **Stream junction**: Stream junctions are points where two or more streams split or meet. Stream junction data consists of reach length across the junctions.
5. **Flow paths**: In a downward direction, flow paths define the center of mass of water flow in the main channel and the overbank areas. It is used to determine reach lengths between cross sections in the left overbank, main-channel, and right over bank (Ackerman *et al.*, 2000). Flow paths were created using the editor tool in HEC-GeoRAS.
6. **Stream centerlines**: This the river reach network used to represent the stream centerline and used to define the main channel flow path. Construction of stream centerline followed an upstream to downstream orientation (See Figure 4.45).

Energy loss coefficients.

In this study, Manning's n values as well as contraction and expansion values were used to determine friction losses and transition losses respectively (Brunner, 2010). The land use layer was used to calculate Manning's n values along the cutlines. Table 4.11 shows the Manning's n coefficient used in this study. Manning's n value was highly variable and depended on surface roughness and vegetation. The default contraction and expansion coefficients of 0.1 and 0.3 were used for all areas of the watershed.

Table 4.11 Manning's n input values used for this study.

Land use type	Manning's coefficient
Urban area	0.04
Forest	0.36
Agricultural area	0.32
Water body	0.05

Steady Flow Data.

Steady flow data consist of flow regime, boundary conditions and runoff peak discharge data. They were required to perform steady state water surface profile computation. Flow data obtained from HEC-HMS was used as input into the model for steady state flow computation.

1. **Flow regime data:** In this study, subcritical flow regime was selected. Computation at cross-sections was done from upstream to downstream. The mixed l flow regime calculated was constrained to critical depth. Hence the channel slope was used to determine the critical depth at the downstream boundary.
2. **Boundary Conditions:** Boundary conditions data were entered to establish a starting water surface at the upstream and downstream ends. Hence, only the downstream end slope values were entered since subcritical flow regime was calculated. In this study, the normal depth (energy slope) values were entered.
3. **Discharge data:** River discharge data estimated in HEC-HMS was obtained and entered to calculate the water surface profile. The values were entered from upstream to downstream of each reach.

4.9.14 Model pre-processing

1. Loading Programs

The process began by opening ArcMap interface and loading HEC-GeoRAS geospatial extension, spatial analyst and 3D Analyst. These were done in order to construct and extract geometric data for modelling in HEC-RAS (Brunner, 2001; Van, 2010). Figure 4.46 shows the menu in the graphical user interface

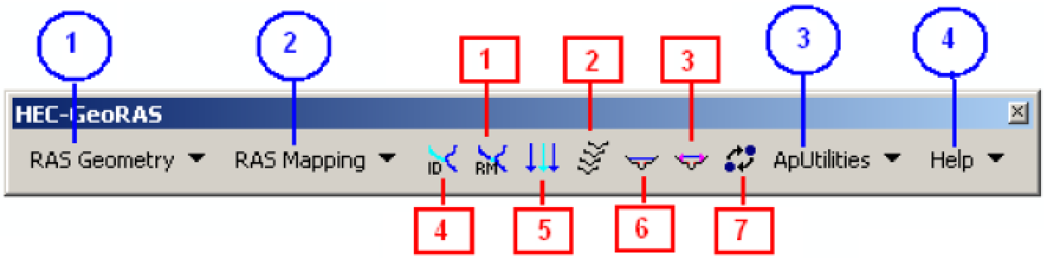


Figure 4.46 HEC-GeoRAS Main Menu. 1, 2 3 and 4 in blue are-the RAS geometry, RAS post processing, utilities and help dropdown menus respectively. Number 1, 2, 3, 4, 5, 6, and 7 in red are the cross section, identity, flowpath, cross-section and file conversion icons respectively.

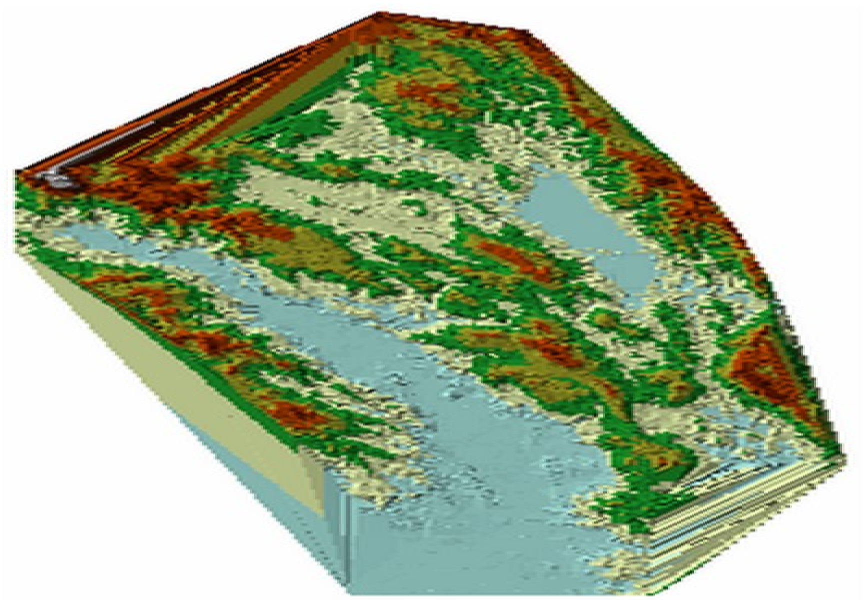


Figure 4.47 Example of the Triangular Irregular Network converted from DEM.

2. DEM Conversion

Before creating the attribute layers, terrain (digital elevation model) data were added to ArcMap and converted into triangular irregular network (TIN), see Figure 4.47.

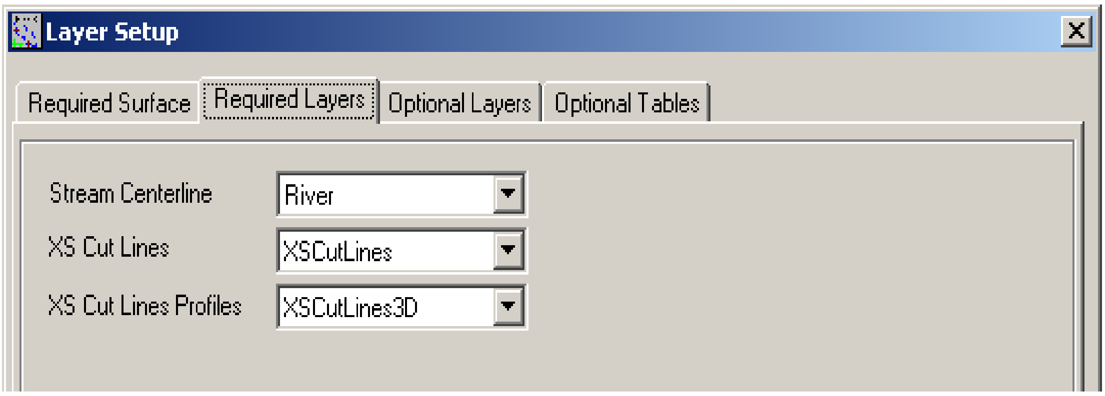


Figure 4.48 TIN layer setup dialogue box with required layers.

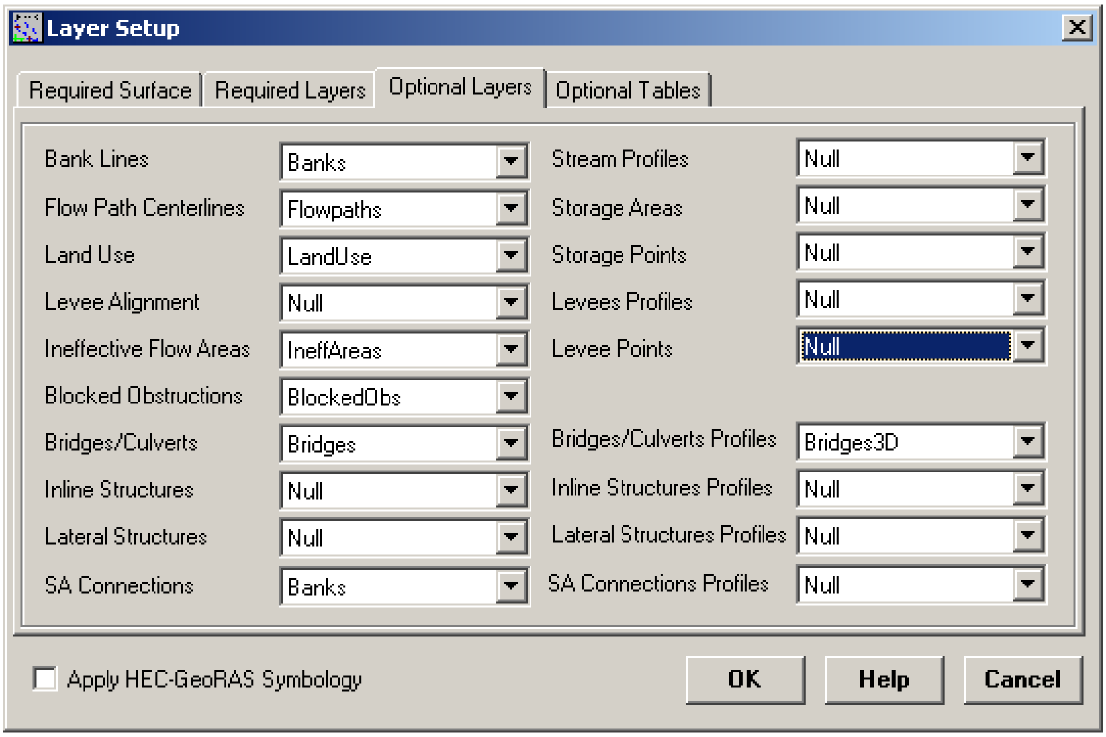
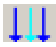


Figure 4.49 Layer setup dialogue box with optional layers.

Creation of layers.

Next, layers were generated for geometric data development. Some layers were basic requirements and others optional layers (see Figure 4.48 and 4.49). The required layers used in this study included: stream centerlines, cross-sectional cutline and profiles (Figure 4.45). Whereas optional layers consist of Flowpath centerlines, Bank lines and Manning's n. In this study hydraulic structures such as bridges/culverts, blocked obstructions, and storage areas were ignored because of the goal of the study.

1. First, stream centerlines were first digitized, then all reaches and rivers were given unique names and IDs. Other attributes in the attribute table included the nodes, hydro IDs, arc length, shape, length, *ToSta* and *FroSta* attributes.
2. Next, Bank lines were digitized to distinguish the main channel from over bank areas.
3. Following creation of Bank lines, Flow paths containing centreline, Left overbank and Right overbank layer was created and labelled with an identifier (Left channel, Main Channel and Right corresponding to the Left, Main channel and Right over bank). This was performed using the assign type  flow path tool. Initially, the left Flowpath line was digitised looking downstream and later the right Flow path was also digitised. Flowpaths digitisation generated line type attributes (Brunner, 2010).
4. Cross sectional cutline layer was subsequently digitised to extract elevation data from terrain data for creating a ground profile across the channels. In this case, intersections of cut lines with already digitised RAS layers such as Centrelines, Bank lines and Flowpaths were used to delineate the main channel from flood plains, downstream reach lengths, bank stations, and Manning's n. To generate the XScutlines feature class, they were drawn from left to right (looking downstream) covering the entire flood plain. The XScutlines were constructed in a direction normal to the stream centerline.
5. This step was succeeded by assigning Manning's n, using a land use feature class maps where Manning's n values for different land use type were stored. In its attribute table the field, Manning's n values with LUCode heading were extracted for each cross section (Brunner, 2001).
6. After all layers had been verified, the *GIS2RAS* export files were exported into the main RAS software for model execution.

4.9.15 Model run.

At this stage, the HEC-RAS was used to create projects and edit the GeoHEC-RAS files. First channel geometry was edited. Next, the imported Manning's data were reviewed and edited for all cross sections. Following that, the contraction and expansion coefficients of 0.1 and 0.3 were entered. Afterward, steady state flow computation was selected which required boundary conditions and flow input data from HEC-HMS for all reaches. Finally, the water surface profile, flood extent and velocity were computed and reviewed before post-processing. Figure 4.51-52 are examples of the channel geometry window in HEC-RAS showing cross-sectional channel geometry. Table 4.12 shows an example of Manning's n entered for each cross-section. Manning's n is a coefficient of surface roughness which accounts for the frictional force and depends on the land cover. In this study Manning's n of 0.04, 0.36, 0.32 and 0.05 were entered for urban, forest, agricultural land and water respectively. Different Manning's n values in each row represent the surface roughness along that cross-section. For example in Table 4.12, five cross-sections were generated for the river reach. Each cross-section could have one or four land cover types along it. However, only 20 Manning's n values can be entered for a cross-section in HEC-HMS.

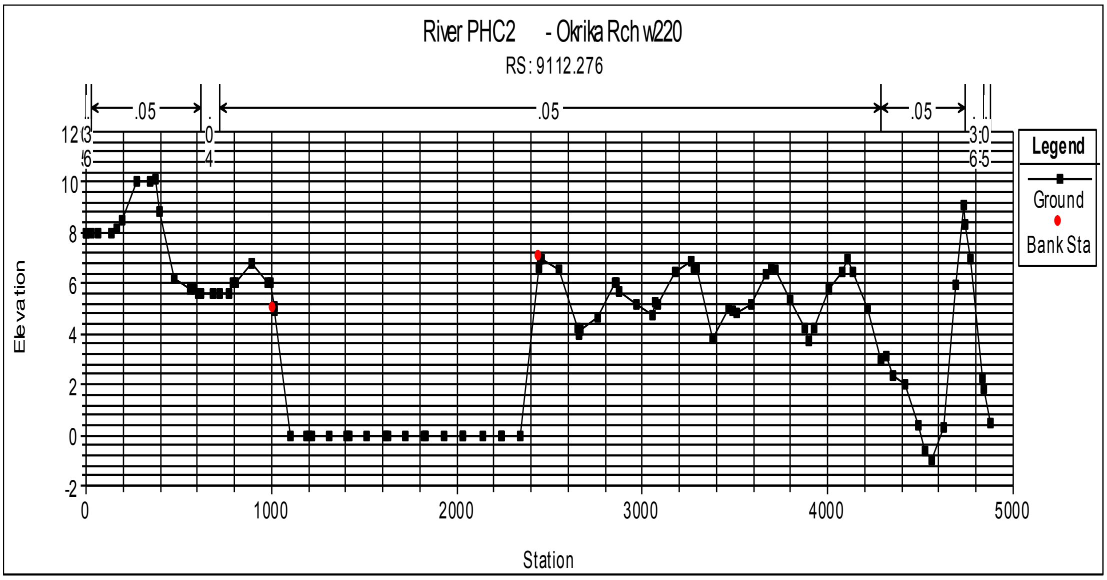


Figure 4.51 Example of cross-section in the Port-Harcourt reach showing channel elevation, width, bank stations and Manning's n values used in the modelling.

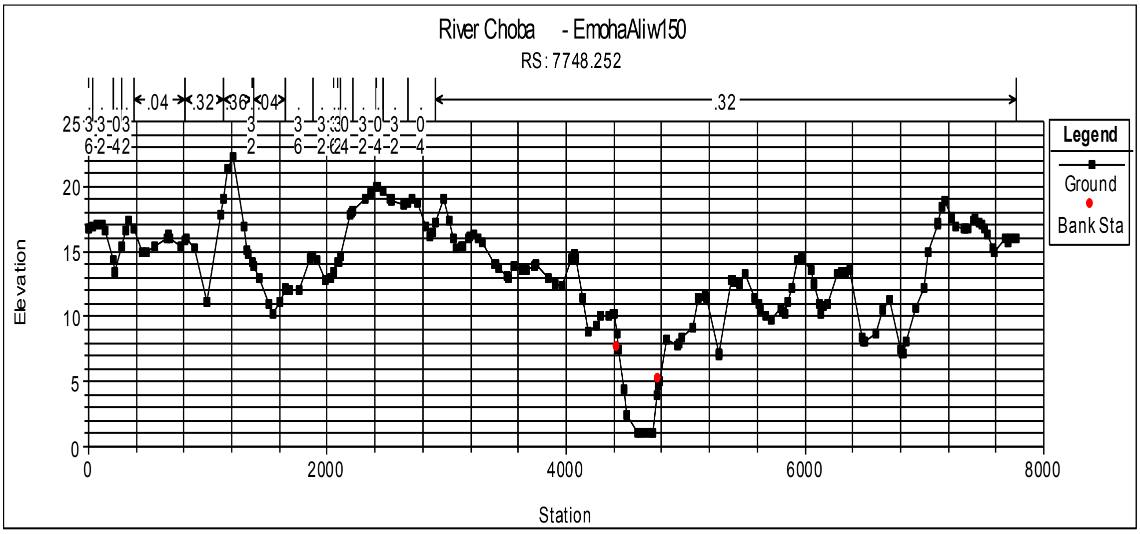


Figure 4.52 Example of cross-section for Choba reach showing channel elevation, width, banks stations and Manning's n values used for modelling.

Table 4.12 An Example of Manning's n Values entered for Bonny river reach for year 2003.

S/n	River Station	Frctn (n/K)	n #1	n #2	n #3	n #4	n #5	n #6	n #7
1	7026.154	n	0.05						
2	5532.808	n	0.05	0.05					
3	4065.607	n	0.05	0.05					
4	2605.353	n	0.05	0.04	0.05				
5	1386.698	n	0.05	0.36	0.05	0.36	0.32	0.36	0.05

4.9.16 Post processing.

After the model run and steady flow computation, post processing (flood mapping) was performed to produce hazard maps for visualisation. Generally, the post processing phase involved two major steps: (1) Data importation and conversion (2) Flood mapping

First, HEC-RAS result data was imported into HEC GeoRAS. The RAS data was first converted from an SDF data format to an XML format which was compatible with ArcGIS. Next, the TIN terrain data were then imported. Hence a new geodatabase was set up for flood inundation mapping. Subsequently, the bounding polygon was generated to define the analysis extent by connecting XScutlines (see Figure 4.53).

Finally, the flood inundation extent was then mapped for the respective historical and future scenarios based on the defined extent. This was then used to generate water surface TIN for the

Figure 4.53 Diagram showing an example of bounding polygon drawn during the post processing stage.

selected profile. The TIN defined a zone connected to the outer points of the bounding polygon meaning that the TIN includes areas outside possible flooding (Figure 4.54).

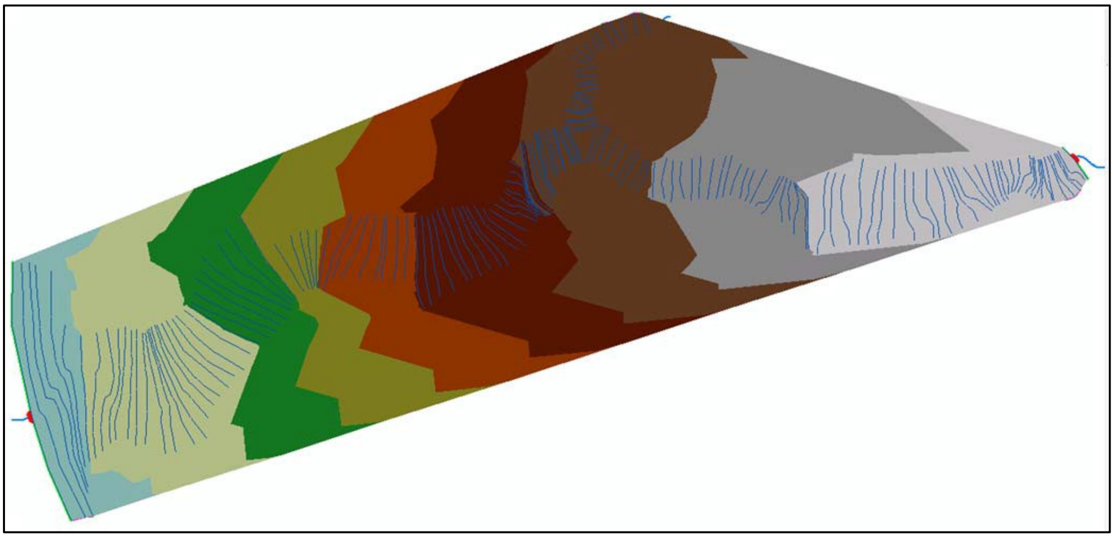


Figure 4.54 Water surface TIN generated during the post processing stage.

In order to determine flood depth, water surface TIN (as in Figure 4.54) was then subtracted from the underlying terrain data. In order to delineate flood plain, areas where the water surface elevation was higher than the terrain elevation were characterized by positive values and was converted to polygon marking flood extents. Meanwhile areas with negative values were characterised as dry (Ackerman *et al.*, 2000; Brunner, 2010).

4.9.17 Model Validation.

Model validation was carried out using visual comparison between satellite map and model map. This validation was done according to Knebl *et al.* (2005) by matching the estimated historical flood extent for January 8, 2003 with model estimations for January 9, 2003. The reason for the one-day difference is because there was no rainfall event for the data the satellite map was acquired for i.e. January 8, 2003. And the model rejected a 0mm rain depth. However, the rain depth of 3.5mm corresponding to January 9 was used for the validation. The assumption was that 3.5mm rain depth is negligible and can represent the river condition of the previous day. Hence validation was done for 9.4 km of the Bonny River channel of which their widths were then compared.

4.10 DATA ANALYSIS.

Data analysis was performed in this study to describe and summarise the results. It was also performed to identify relationships between variables, compare variables, and identify the difference between variables and forecast outcomes. In this study sigma plot data analysis software was used to analyse data. Hence, data analysis techniques applied involved, the One-way ANOVA, Two-way ANOVA, and multivariate and regression statistical analysis techniques. The ANOVA techniques were useful in this study for analysing the significance of the difference between the means of more than two groups (Kothari, 2004). That is, the ANOVA technique was important for comparing the differences in more than one population. In a two or more way ANOVA, the interaction (i.e., interrelation between two independent variables/factors), if any, between two independent variables affecting a dependent variable can as well be studied (Kothari, 2004). In this study, it was used to compare the difference between historical and future peak flows of different time periods. The statistical difference observed were considered significant when $P < 0.05$. The Regression analysis was used for explaining the relationship between the output or response or dependent variables and the input, predictor or independent or explanatory variables (Faraway, 2002). In this study regression was specifically used for determining the design storm, accessing the model validation as well as checking the relationship between sub-basins.

Chapter 5. Urban Land-use & Land-cover dynamics in Greater Port-Harcourt Watershed.

5.1 INTRODUCTION.

Urban flooding mainly linked to rainfall and LULC change is presently an issue in the GPH area as discused in detail in Chapter one. Urban LULC changes resulting from planned or unplanned developments is one of the key drivers of flooding and can have severe implications for exposed elements at risk (Zanganeh *et al.*, 2011; Jha *et al.*, 2012; Tripathi *et al.*, 2014; Hegazy and Kaloop, 2015). Therefore, the estimation of LULC change using multi-temporal satellite data is valuable for modelling flood impacts or watershed responses to LULC changes. As highlighted in chapter one, the rapid rate of urbanisation in developing countries has drawn much attention (Jha *et al.*, 2012; Munji *et al.*, 2013; Elalem and Pal, 2014). Other setbacks include the lack of extensive research for watersheds in developing countries (Parker, 2000a). Port-Harcourt is a sensitive and dynamic wetland environment prone to flooding, and the rapid rate of urbanisation has been re-echoed in recent studies (Obinna *et al.*, 2010; Mmom and Fred-Nwagwu, 2013; Elenwo and Efe, 2014; Enaruvbe and Ige-Olumide, 2014). Two main studies have examined historical changes in LULC, but no attempt have been made to estimate future urban changes. As highlighted in Chapter 1, two previous studies by Wizor (2014) and Enaruvbe and Ige-Olumide (2014) mainly focused on the extent and nature of historical LULC changes but did not cover the entire watershed. This study further examines the process or type of change involved, their tendency to expand or contract and change intensities, with a focus on the whole watershed system.

This chapter presents the data analysis and discusses the LULC dynamics in the study area. As stated in Chapter 1, the primary questions addressed here are:

- What are the historical and future changes in the LULC of Greater Port-Harcourt Watershed?
- To what extent could afforestation reduce flooding in the GPH watershed?

The secondary research questions addressed here are - *What was the extent and nature of historical LULC changes? What is the extent of future urban LULC change due to the implementation of the plan by 2060? What are the dominant forces of LULC change in the watershed? To what extent could afforestation reduce flooding?* The main objective was to understand the LULC change dynamics over the GPH watershed aimed to highlight the extent, nature and process of changes in the watershed. The chapter is structured into six major sections. Next section recaps on the materials & methods stated in Chapter 4, followed by the result and discussion section, and finally a concluding section.

5.2 MATERIALS AND METHOD.

This study adopted the post-classification change detection approach. The maximum likelihood classification method was applied for classifying maps. Supervised classification was performed for the 1986 (TM) and 2003 (ETM+) satellite imageries from the USGS. This method was capable of evaluating the nature of change and provide information such as "from to" and to changes from the matrix, as well as percentage change, gross gain, gross loss, total change, persistence plus swap and net change percentages (Pontius et al., 2004; Al-doski *et al.*, 2013; Mmom and Fred-Nwagwu, 2013; Enaruvbe and Ige-Olumide, 2014). The procedure followed involved the geometric rectification, image enhancement, and maximum likelihood classification. Subsequently, change detection was performed and involved the comparison of the corresponding classes or themes to identify areas where change had occurred in historical maps. In short, the extent and nature of change were identified. Changes to the future urban area were determined by overlaying the GPH Masterplan map on the 2003 baseline map (refer to chapter four for a detailed account of steps taken during the LULC analysis).

5.3 RESULT

This section presents results obtained from the map classification, change detection and statistical analysis performed.

5.3.1 Analysis of the Extent of Historic LULC changes between 1986 and 2003

Visual interpretation

Figures 5.1, 5.2 and 5.3 present the classified LULC maps of GPH the watershed. The maps were for 1986, 1995 and 2003 time periods. Before estimating the extent of change, the extent of urban expansion was analysed based on the visual representation of individual maps. As detailed in Chapter 4, the 1986 and 2003 maps were classified using the supervised classification method while the 1995 pre-classified map was reclassified in this study.

Generally, LULC classes compared include urban area, forest, agricultural land, mangrove and water.

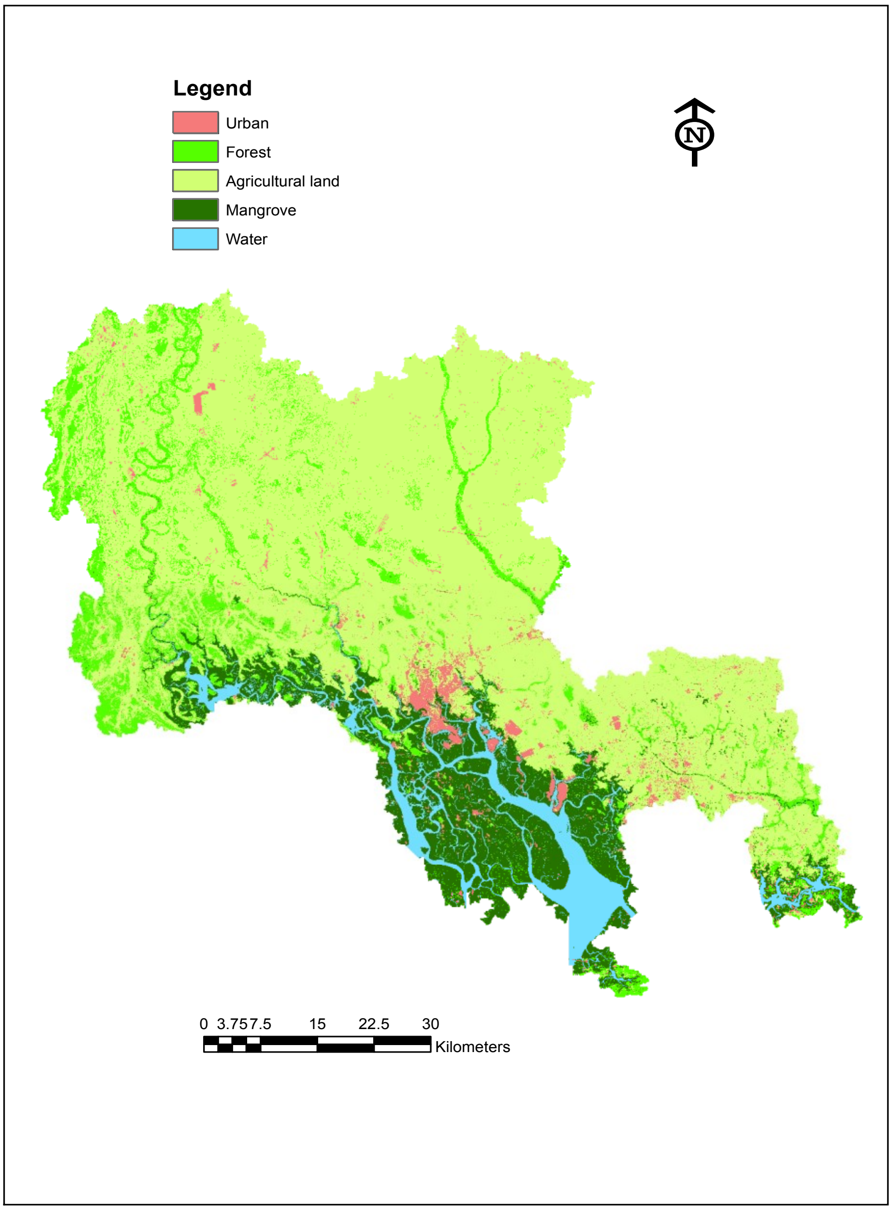


Figure 5.1 Classified LULC map of Greater Port-Harcourt Watershed for 1986. LULC classes include: Urban area, Forest, Agricultural Land, Mangrove and Water (Source: USGS).

From the maps, the changes in the extent and pattern of the urban class (in light brown colour) clearly indicate that urban expansion occurred historically between 1986 and 2003. A multi-date comparison of Figure 5.1-5.2 indicates that urban expansion took place between 1986 and 1995. Visually, the Figure 5.2 shows that the initial growth occurred around the old

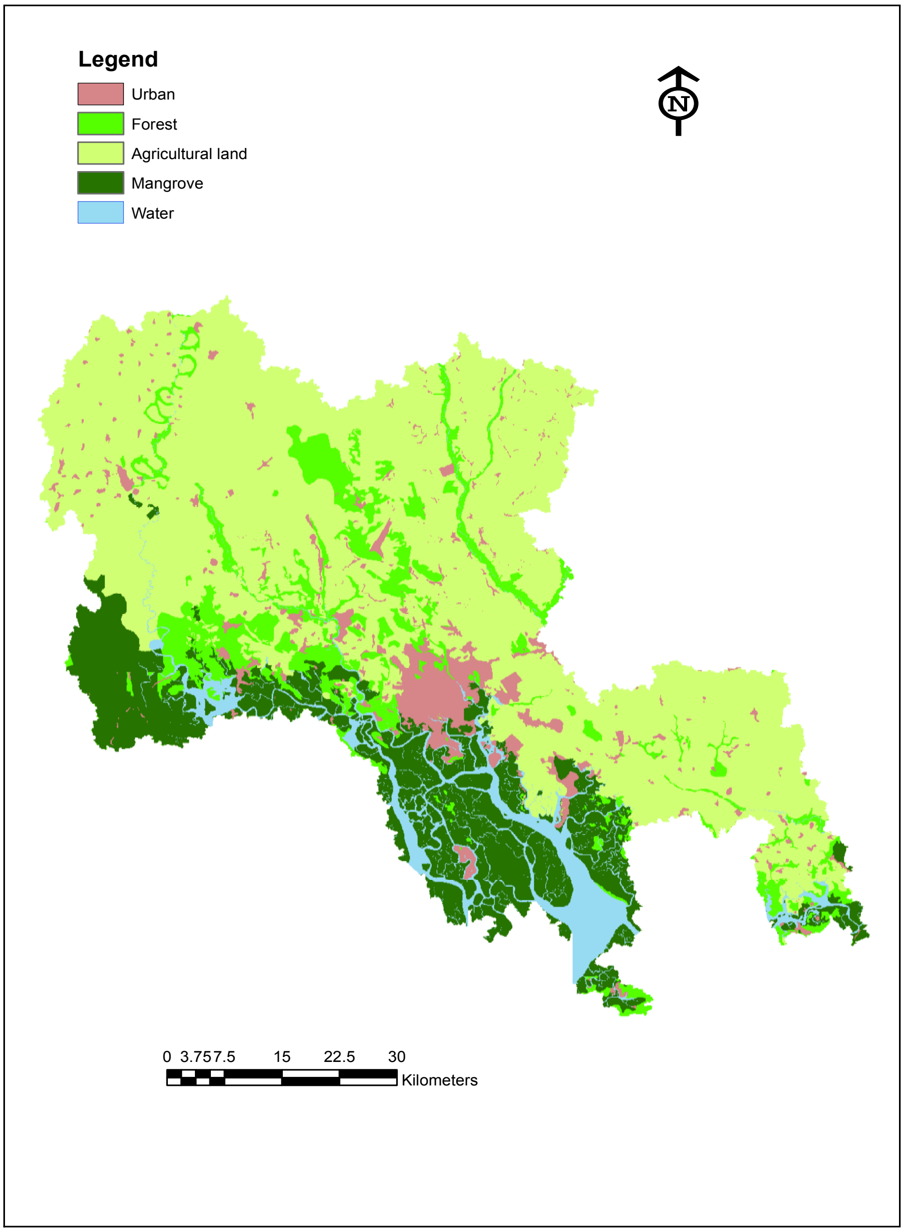


Figure 5.2 Classified LULC map of Greater Port-Harcourt Watershed for 1995. LULC classes include: Urban, forest, agricultural land, mangrove and water. (Source: Rivers State Ministry of Land and Housing).

Port-Harcourt City. Similarly, Figure 5.3 demonstrates that additional urban expansion occurred between 1995 and 2003; in contrast, the urban area was more widespread. For other classes, the maps demonstrate that agricultural land was the dominant class. It covers most areas except the southern axis. Water and mangrove occupied most parts of the southern axis, whereas forest was scattered all over the watershed but in patches.

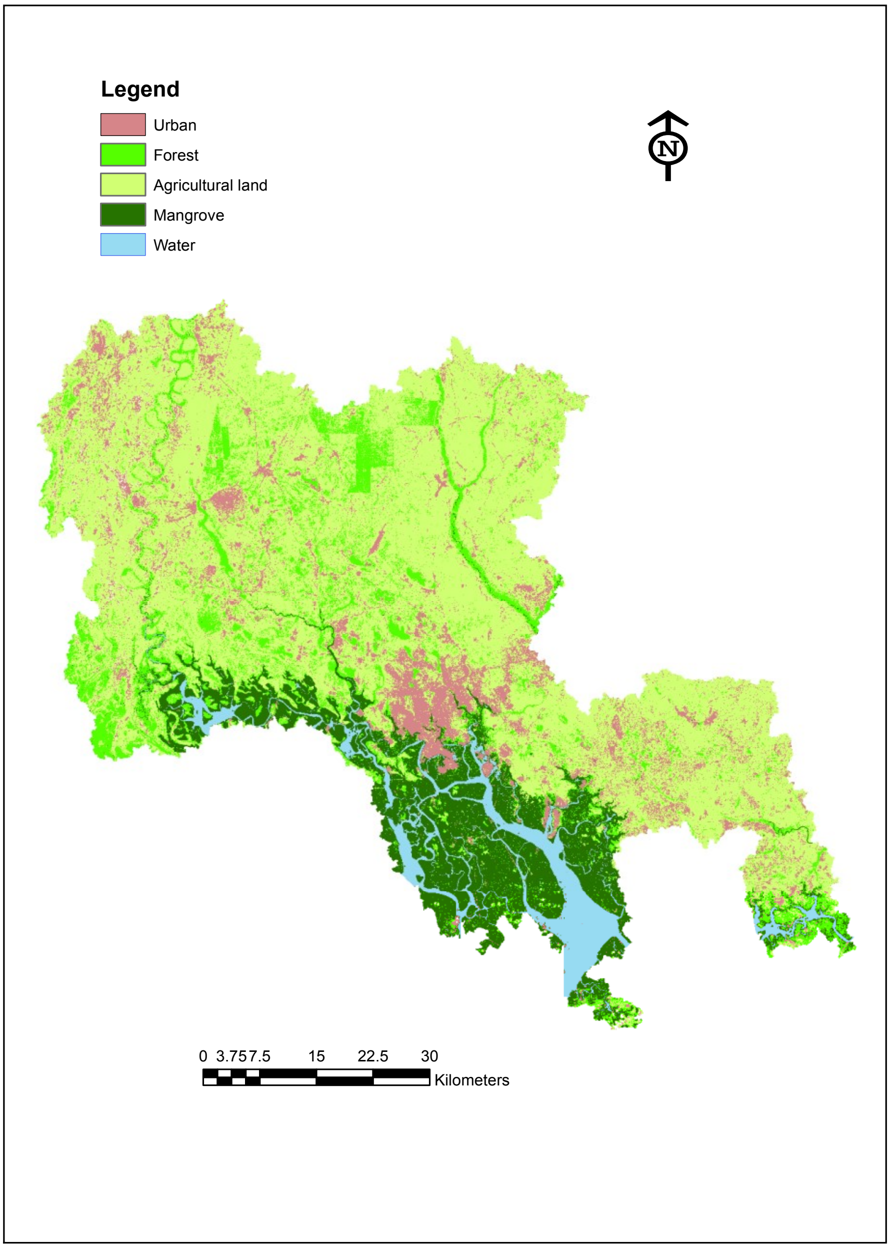


Figure 5.3 Classified LULC map of Greater Port-Harcourt Watershed for 2003. LULC classes include urban area, forest, agricultural mangrove and water (Source: USGS).

5.3.2 Analysis of Extent of Change-Urban and other Land-use/Land-cover categories.

Tables 5.3 to 5.5 presents the result of the extent of historical changes in LULC categories. First, the bar chart and line graph of urban extent are presented in Figure 5.4. Hence the line graph clearly indicates that there was a significant change in the extent of urban LULC between 1986 and 2003. Table 5.3 shows that a significant change of about 309 % occurred because urban area expanded from about 134.5 km^2 in 1986 to about 550km^2 in 2003. Based on this value, the growth was about 24 km^2per annum within the entire period. Figures 5.4 to 5.7 provide the graphical representation of the extent, the proportion of change in addition to the percentage and area change. The graph in Figure 5.4 shows that drastic expansion of the urban LULC area occurred, while the bar chart show a continuous rise in the proportion of urban area from as little as 2.8% in 1986 to about 11.4% of the total watershed area in 2003.

Table 5.1 Changes in the area of LULC between 1986 and 2003. Map shows urban area experienced a drastic change by about 300%.

Class Name	1986		2003		Change	
	%	Km^2	%	Km^2	Km^2	%
Urban	2.8	134.5	11.4	550.0	415.5	308.9
Forest	12.5	600.2	10.9	526.5	-73.7	-12.3
Agric. Land	65.9	3174.6	59.9	2885.5	-289.2	-9.1
Mangrove	13.2	636.4	12.9	622.3	-14.1	-2.2
Water	5.7	275.3	4.9	236.7	-38.6	-14.0
Total		4821.0		4821.0		

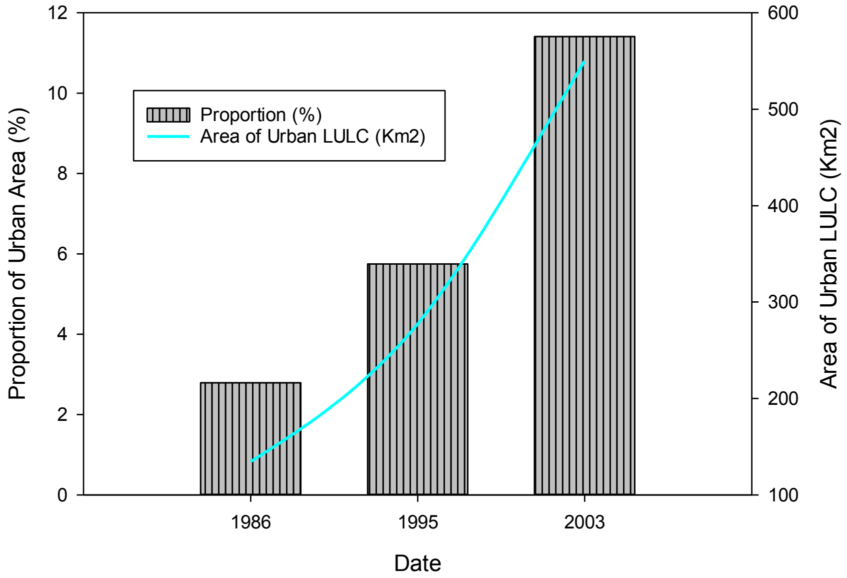


Figure 5.4 Proportion and trend of urban area changes between 1986 and 2003. The bar chart presents the proportion of urban area for the respective dates. The line graph shows the trend and change in urban land-use area.

An intertemporal comparison of 1986-1995 and 1995-2003 periods clearly reveal that drastic shifts in urban area occurred in both periods (Figure 5.4, Table 5.4 and Table 5.5). The percentage change in urban area in both periods was almost the same, hence percentage change in the first period (1986-1995) was slightly higher than in the subsequent period (1995-2003). However, in terms of the actual area changed (in km^2), urban expansion was greater in the latter than in the initial period. That is, about 272.7 km^2 expansion (from approximately 277.3 km^2 to 550 km^2) in the latter in contrast to about 143 km^2 experienced in the initial period (from approximately 134.5 to 277.3 km^2). This indicates that urban expansion was drastic in both periods but more significant in the later period. Although, Tables 5.4 and 5.5 show that the percentage change in both periods were almost equal and drastic, the annual growth rate of the latter period (i.e. about 34 km^2 per year) was higher than the rate of the former period (at about 16 km^2 per year). In a nutshell, significant urban growth occurred in both periods,

Table 5.2 Changes in the area of LULC between 1986 and 1995. Table shows urban area experienced a significant increase in urban area.

Class Name	1986		1995		Change	
	%	km^2	%	km^2	km^2	%
Urban	2.8	134.5	5.8	277.3	142.8	106.1
Forest	12.5	600.2	11.1	534.6	-65.6	-10.9
Agric. Land	65.9	3174.6	60.1	2896.2	-278.4	-8.8
Mangrove	13.2	636.4	16.9	812.8	176.5	27.7
Water	5.7	275.3	6.2	300.1	24.8	9.0
Total		**4821.0**		**4821.0**		

Table 5.3 Changes in the area of LULC between 1995 and 2003. Table shows urban area experienced a significant increase in urban area.

Class Name	1995		2003		Change	
	%	km^2	%	km^2	km^2	%
Urban	5.8	277.3	11.4	550.0	272.7	98.4
Forest	11.1	534.6	10.9	526.5	-8.1	-1.5
Agric. Land	60.1	2896.2	59.4	2862.5	-33.7	-1.2
Mangrove	16.9	812.8	12.9	622.3	-190.5	-23.4
Water	6.2	300.1	4.9	236.7	-63.4	-21.1
Total		**4821.0**		**4821.0**		

Figure 5.5 displays the extent, proportion and the trend of all LULC categories for 1986, 1995 and 2003. The group bar chart clearly demonstrates that agricultural land was the most dominant land cover in the watershed historically, followed by mangrove, and then forest. The urban area was among the smallest LULCs in terms of extent. In terms of trend, agricultural land declined over time; however, it remained the largest and was significantly higher than all other LULC types in terms of extent and average proportion. On the other hand, urban LULC was averagely the smallest in terms of proportion. The bar chart clearly demonstrates that the percentage of urban LULC increased progressively whereas the proportion of forest and agricultural land declined progressively. For example, the percentage of urban area increased from about 2.1%, through 5.8%, to about 11.4%, respectively, whereas the percentage of agricultural land decreased from about 65.9% to about 60.1% and from about 60.1% to approximately 59.4%. In summary, only the urban area exhibited progressive expansion.

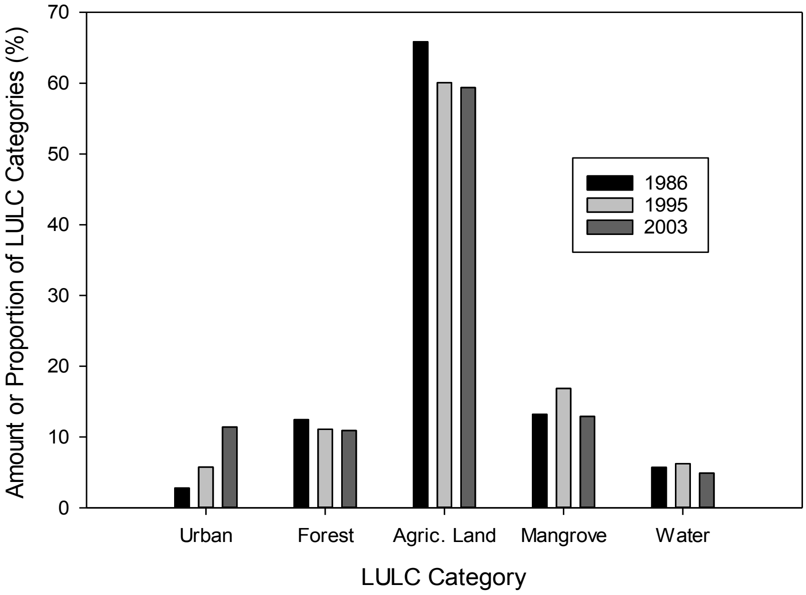


Figure 5.5 Group bar chart showing the proportion of LULC categories in 1986, 1995 and 2003.

In terms of general trends within the entire study period, except for mangrove, Figures 5.6, 5.7, and 5.8 demonstrate that the extent of urban area increased while the extent of other classes declined. Figure 5.6 showed that the percentage of change in the urban area was significantly higher than that of other categories. Moreover, Figure 5.7 showed that all other classes apparently experienced a negative change while urban area experienced a positive change.

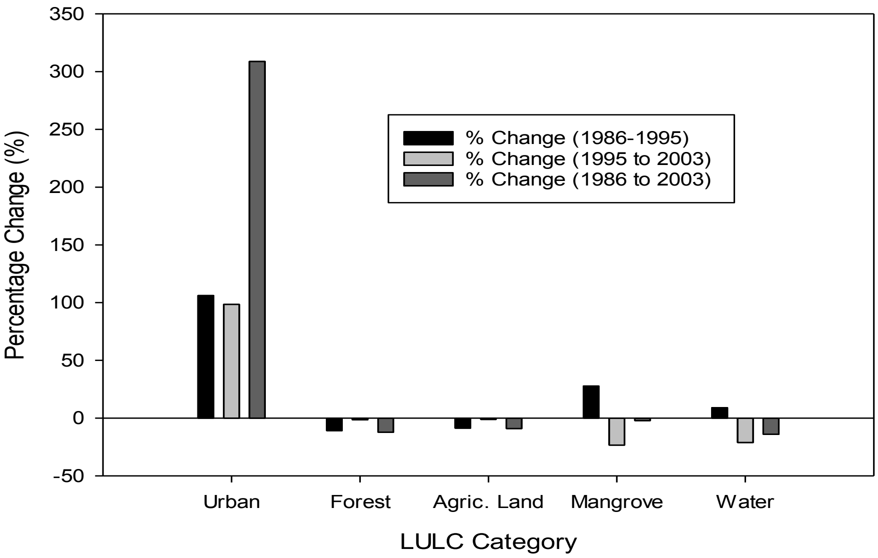


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Figure 5.6 Bar chart showing Percentage Change of LULCs from 1986 to 1995, 1995 to 2003, and 1986 to 2003

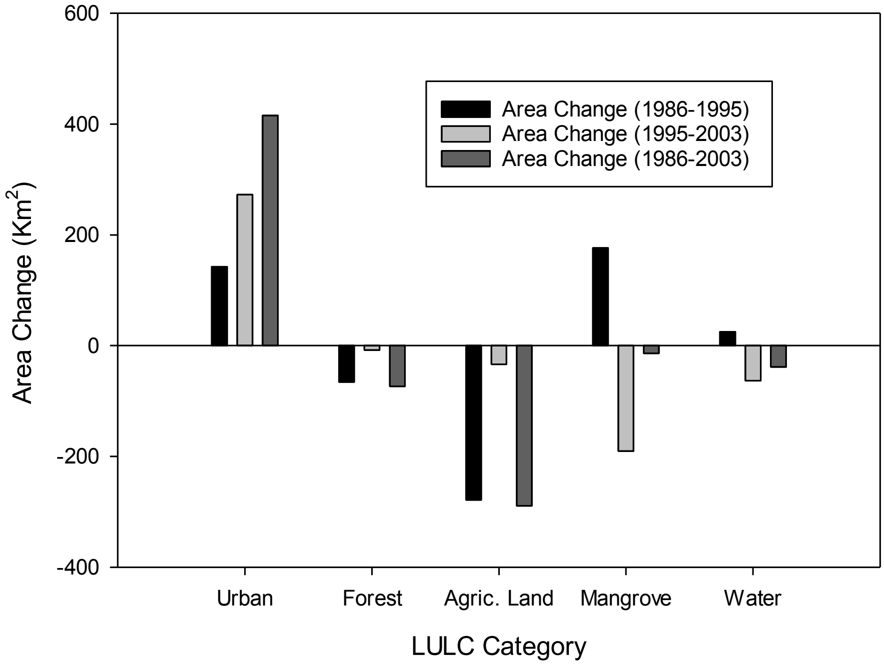

Figure 5.7 Bar chart showing LULC Change area from 1986 to 1995, 1995 to 2003, and 1986 to 2003.

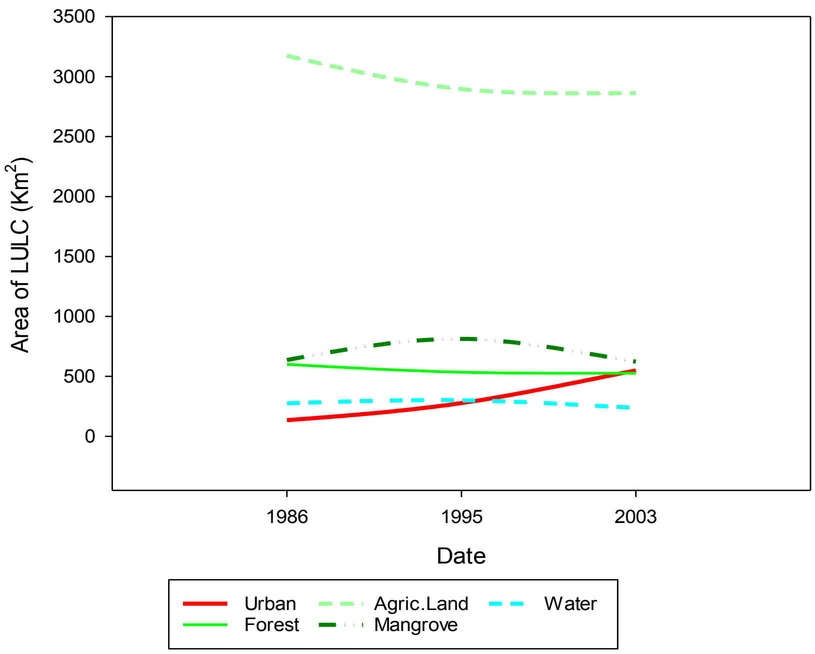

Figure 5.8 Line graph showing growth and trend of LULC expansion/reduction in the LULC maps.

5.3.3 Analysis of the Nature of Change-Urban and other Land-use/Land-cover categories.

Based on the cross tabulation matrices, this subsection examines the prominent transitions from one category to another. Table 5.6 displays the transition matrix consisting of the total and inter-category conversions of LULCs from 1986 to 2003, while Tables 5.7 and 5.8 display the same for 1986-1995 and 1995-2003 periods. Cross tabulation was achieved using a tabulate area tool in Arc map. Note: the rows display the categories of time 1, whereas the columns show the categories of time 2. Row totals at the right signify the proportion of the landscape by LULC category in Time 1 and the column totals at the bottom represent the proportion of landscape by category in Time 2. As a first step, the off-diagonal entries were analysed, followed by the total columns and rows, then the persistence, gross gains, losses and lastly the net and swap changes.

Urban related transitions.

In terms of urban related transition, based on the results, it is clear that the urban area significantly increased mainly at the expense of agricultural land. Results show that the conversion of all LULC categories to urban area led to a total of about 549km^2 in urban area between 1986 and 2003; hence, the most prominent transition embroils the conversation of agricultural land (about 422km^2) to urban areas. That means about 93.3% of all conversions to urban land resulted from agricultural land. In contrast, transition from other LULC classes to urban areas were relatively very low. For example, the transition from mangrove, forest and water to urban area were only about 15.3%, 13.3% and 1.9% respectively.

Table 5.4 Land-cover transition matrix of Greater Port-Harcourt watershed area, 1986 to 2003, based on post-classification of Landsat satellite imageries.

LULC_CATEGORY	URBAN	FOREST	AGRIC_LAND	MANGROVE	WATER	1986 Total	1986 Gross Loss
Urban	97.2	5.1	27.3	4.8	0.1	134.5	37.3
Forest	13.3	242.4	321.0	23.3	0.3	600.2	357.8
Agric. Land	422.3	229.5	2520.3	2.6	0.0	3174.6	654.4
Mangrove	15.3	49.4	16.7	550.8	4.3	636.4	85.6
Water	1.9	0.2	0.3	40.9	232.0	275.3	43.3
2003 Total	550.0	526.5	2885.5	622.3	236.7	4821.0	
2003 Gross Gain	452.8	284.2	365.2	71.6	4.7		

Similarly, Figures 5.7 and 5.8 display a similar pattern in terms of conversion of other classes to urban area. In both periods, the transition from agricultural land to urban area was the most prominent. However, the conversion of agricultural land to urban was higher in the later period (1995-2003) than in the former (1986-1995). Moreover, the transition from forest and mangrove were negligible in both periods. As expected, the transition from water to urban was the lowest and very insignificant.

Table 5.5 Land-cover transition matrix of Greater Port-Harcourt watershed area, 1986 to 1995, based on post-classification of Landsat satellite imagery and RivMoLH LULC Polygon map data.

LULC CATEGORY	URBAN	FOREST	AGRIC.LAND	MANGROVE	WATER	1986 Total	1986 Gross Loss
Urban	71.1	4.0	41.3	15.1	3.1	134.5	63.4
Forest	6.7	189.7	258.6	135.2	10.1	600.2	410.6
Agric. Land	181.5	300.4	2552.7	134.1	5.9	3174.6	621.9
Mangrove	14.4	37.8	41.2	481.5	60.1	635.0	153.5
Water	3.5	2.7	2.5	47.0	220.9	276.7	55.7
1995 Total	277.3	534.6	2896.2	812.8	300.1	4821.0	
1995 Gross Gain	206.2	344.9	343.5	331.4	79.2		

Table 5.6 Land-cover transition matrix of Greater Port-Harcourt watershed area, 1995 to 2003, based on post-classification of RivMoLH LULC Polygon map data and Landsat satellite imagery.

LULC_CATEGORY	URBAN	FOREST	AGRIC.LAND	MANGROVE	WATER	1995 Total	1995 GROSS LOSS
Urban	163.0	8.3	91.8	12.1	2.0	277.3	114.3
Forest	26.9	151.7	325.1	29.3	1.6	534.6	382.9
Agric. Land	326.2	226.1	2317.5	24.8	1.6	2896.2	578.7
Mangrove	28.4	129.5	145.0	481.2	28.9	812.8	331.7
Water	5.6	11.0	6.1	74.9	202.6	300.1	97.5
2003 Total	550.0	526.5	2885.5	622.3	236.7	4821.0	
Gross Gain	387.0	374.8	568.0	141.2	34.1		

Non-urban related transitions.

Tables 5.7 reveal that the prominent non-urban shifts were from forest to agricultural land (about 321km^2) and from agricultural land to forest land (about 229.5km^2) between 1986 and 2003. Similarly, the transition from agricultural land to forest and vice versa were the notable non-urban LULC transitions in the two periods studied. However, the conversion of forest to agricultural land accelerated between 1995 and 2003. Also, the conversion of 135 km^2 of forestland to mangrove was another notable shift between 1995 and 2003. Furthermore, the conversion of mangrove to forest and mangrove to agricultural land were significant. Generally, non-urban transitions were more significant in the later period than in the former.

Table 5.7 Land-use/Land-cover Conversion showing the Nature of changes between the different time periods.

LULC Conversion type	1986 to 2003	1986 to 1995	1995 to 2003
Urban to Urban	97.2	71.1	163.0
Urban to Forest	5.1	4.0	8.3
Urban to Agric. Land	27.3	41.3	91.8
Urban to Mangrove	4.8	15.1	12.1
Urban to Water	0.1	3.1	2.0
Forest to Urban	13.3	6.7	26.9
Forest to Forest	242.4	189.7	151.7
Forest to Agric. Land	321.0	258.6	325.1
Forest to Mangrove	23.3	135.2	29.3
Forest to Water	0.3	10.1	1.6
Agric. Land to Urban	422.3	181.5	326.2
Agric. Land to Forest	229.5	300.4	226.1
Agric. Land to Agric. Land	2520.3	2552.7	2317.5
Agric. Land to Mangrove	2.6	134.1	24.8
Agric. Land to Water	0.0	5.9	1.6
Mangrove to Urban	15.3	14.4	28.4
Mangrove to Forest	49.4	37.8	129.5
Mangrove to Agric. Land	16.7	41.2	145.0
Mangrove to Mangrove	550.8	481.5	481.2
Mangrove to Water	4.3	60.1	28.9
Water to Urban	1.9	3.5	5.6
Water to Forest	0.2	2.7	11.0
Water to Agric. Land	0.3	2.5	6.1
Water to Mangrove	40.9	47.0	74.9
Water to Water	232.0	220.9	202.6
Totals	4821.0	4821.0	4821.0

Analysis of landscape persistence and components of change.

Tables 5.8, 5.9 and 5.10 present statistics of LULC components derived from the extended cross tabulation matrices of three periods: 1986-2003, 1986-1995 and 1995-2003. It includes the gross gains and gross losses, total persistence of change, total change, net change, swap change and loss- and gain-to-persistence ratios. In this study, 1986-2003, 1986-1995 and 1995-2003 were the entire historical period, initial period and final period respectively. As shown in Pontius *et al*., (2004), gross gain in this study was calculated by subtracting the persistence from the column total, whereas the gross loss was derived by subtracting the persistence from the row total. Total change is the sum of its gross gain and gross loss, while net change for a category is the difference between the gross gain and gross loss. Next, swap change for an LULC category is the total change minus the net change in the category. Lastly, total loss-to-persistence and gain-to-persistence ratio were also derived to evaluate the tendency of respective LULC classes to lose and to gain from each other.

As shown in Figure 5.8, all LULCs (the entire landscape) made a total gross gain of about 1178.4 km^2, which is about 25% of the watershed. A gross gain of one category is accompanied by a gross loss of another category; hence, the total gross gain is equal to the total gross loss in a landscape. On the other hand, the landscape exhibited persistence of about 75.6% (Appendix 5.1). In other words, about 25% of the watershed experienced the transition from one LULC category to the other within the historical period. Persistence of the landscape declined from 72.9% between 1986 and 1995 and to about 68.8% between 1995 and 2003. Gross gain and gross loss resulted in a total change of about 48.8% of the entire watershed area; however, the total absolute net change experienced was only about 17%. Remarkably, about 31% of the entire watershed experienced a swap change. That is the landscape experienced more swapping change in the later period than in the former. In general, the entire landscape experienced more persistence than transition. Considering the total area changed, the landscape experienced more swap change than net change.

Table 5.8 Statistics of LULC components (gains and losses) and persistence of change in Greater Port-Harcourt Watershed area, between 1986 and 2003.

LULC Category	Gross Gain	Gross loss	Persistence	Total Change	Value of Net Change	Absolute Value of Net Change	Swap change
Urban	452.8	37.3	97.2	490.1	415.5	415.5	74.7
Forest	284.2	357.8	242.4	642.0	-73.7	73.7	568.3
Agric. Land	365.2	654.4	2520.3	1019.6	-289.2	289.2	730.4
Mangrove	71.6	85.6	550.8	157.2	-14.1	14.1	143.1
Water	4.7	43.3	232.0	48.0	-38.6	38.6	9.4
Total	**1178.4**	**1178.4**	**3642.6**	**2356.8**	**0.0**	**830.9**	**1525.9**

Table 5.9 Statistics of LULC components (gains and losses) and persistence of change in Greater Port-Harcourt Watershed area, between 1986 and 1995.

LULC Category	Gross gain	Gross loss	Persistence	Total Change	Value of Net Change	Absolute Value of Net Change	Swap change
Urban	206.2	63.4	71.1	269.6	142.8	142.8	126.8
Forest	344.9	410.6	189.7	755.5	-65.6	65.6	689.9
Agric. Land	343.5	621.9	2552.7	965.4	-278.4	278.4	687.0
Mangrove	331.4	153.5	481.5	484.9	177.8	177.8	307.0
Water	79.2	55.7	220.9	134.9	23.5	23.5	111.4
Total	**1305.1**	**1305.1**	**3515.9**	**2610.3**	**0.0**	**688.1**	**1922.2**

Table 5.10 Statistics of LULC components (gains and losses) and persistence of change in Greater Port-Harcourt Watershed area, between 1995 and 2003.

LULC Category	Gross Gain	Gross Loss	Persistence	Total Change	Value of Net Change	Absolute Value of Net Change	Swap
Urban	387.0	114.3	163.0	501.3	272.7	272.7	228.6
Forest	374.8	382.9	151.7	757.7	-8.1	8.1	749.7
Agric. Land	568.0	578.7	2317.5	1146.7	-10.7	10.7	1135.9
Mangrove	141.2	331.7	481.2	472.8	-190.5	190.5	282.3
Water	34.1	97.5	202.6	131.6	-63.4	63.4	68.2
Total	**1505.0**	**1505.0**	**3315.9**	**3010.1**	**0.0**	**545.4**	**2464.7**

5.3.4 Analysis of Inter-category persistence and components of change.

Again, Tables 5.10-5.12 present the inter-category transitions, while Tables 5.13-5.15 present the values in ranks and Table 5.16 display the Loss-to-and-Gain-to-persistence ratios. Also, Appendix 5.2 presents values of land-use change intensities. Between 1986 and 2003, the result in Table 5.13 indicates that urban area with the highest intensity made the grossest gain (of about 452.8km^2) followed by agricultural land (of about 365.2km^2). At the same time, agricultural land experienced the highest gross loss of about 654.4 km^2 by a huge margin, followed by mangrove (about 257.8 km^2). Similarly, agricultural land experienced the highest persistence followed by forest and then urban. In fact, the persistent agricultural areas made up about 52% of the total watershed and accounts for about 70% of all LULCs that persisted, indicating that the persistence of agricultural land predominates this watershed.

In contrast, between 1986 and 1995, Table 5.14 shows that forestland made the grossest gain (of about 345 km^2) followed by agricultural land (approximately 345km^2), whereas in the latter period (i.e. between 1995 and 2003), agricultural land made the most gain (of about 570 km^2) and afterwards, forest (approximately 375km^2). However, both agricultural land and forest experienced significant gross losses that resulted in small net changes. In contrast, despite the position of urban land in the ranking, the urban area experienced a substantial gross gain with a low gross loss. This placed it as the class with the highest absolute net change between 1995 and 2003. That means urban land increased from about 4.3% initially and later to roughly 8.1% of the entire watershed. Other notable changes between the former and later periods include the high persistence of agricultural land in both periods. However, persistence of agricultural land was lower in the latter (roughly 48.1%) than in the former (about 52.9%). In a nutshell, high gross gains and losses for agricultural land and forest resulted in lower net changes, while high gross gain and lower gross loss for urban land resulted in high net change. Also, the landscape was more dynamic in the later period than in the former in terms of total change.

Inter-category Net and Swap Change.

The net change is equal to the difference between the gross gain and gross loss for a category while swap change is the difference between the total change and net change. Although agricultural land and forest experienced the bulk of the total changes, urban area exhibited the highest actual net change. Agricultural land and forest LULC types experienced more swap-type of change between 1986 and 2003, this accelerated between 1995 and 2003, whereas, urban land and water experienced minimal swap change between 1986 and 2003. Agricultural land experienced bulk of the swap change covering 15% of the entire watershed, which accelerated in the later period. In summary, the results show that although agricultural land experienced the bulk of the total change, a higher percentage of the change was a swap type change than net type of change. In contrast, urban LULC exhibited a considerable total change, and the bulk of the change was a net-type change type rather than swap-type change.

Tendency to change: Loss-to-persistence and gain-to-persistence ratio.

Loss-to-persistence ratio and gain-to-persistence ratios were derived by calculating loss over persistence and gain over persistence for each category. The result indicates that the gain-to-persistence ratio is greater than one (>1) for urban and forest categories which suggest that urban and forest land had a higher tendency to expand than persist between 1986 and 2003. Urban land experienced the most prominent gain-to-persistence ratio (4.7), demonstrating that the urban area was more prone to expand than persisting compared to all other LULCs. Meanwhile, the result for forest land was two-tailed. Forest showed a high gain-to-persistence and a high loss-to-persistence of 1.2 and 1.5 respectively, indicating that forest had a high tendency to expand and the highest tendency to decline. Also, mangrove and water were the least LULCs prone to expand. These trends were largely the same for the initial and later periods analysed in this study.

Table 5. 13 Ranking of gross gains, gross losses, persistence, total change and swap change of LULC categories between 1986 and 2003.

	Gross Gain		Gross Loss		Persistence		Total Change		Absolute Net Change		Swap Change	
	Urban	452.8	Agric. Land	654.4	Agric. Land	2520.3	Agric. Land	1019.6	Urban	415.5	Agric. Land	730.4
	Agric. Land	365.2	Forest	357.8	Mangrove	550.8	Forest	642.0	Agric. Land	289.2	Forest	568.3
1986-2003	Forest	284.2	Mangrove	85.6	Forest	242.4	Urban	490.1	Forest	73.7	Mangrove	143.1
	Mangrove	71.6	Water	43.3	Water	232.0	Mangrove	157.2	Water	38.6	Urban	74.7
	Water	4.7	Urban	37.3	Urban	97.2	Water	48.0	Mangrove	14.1	Water	9.4
	Total	1178.4	Total	1178.4	Total	3642.6	Total	2356.8	Total	830.9	Total	1525.9

Table 5. 14 Ranking of gross gains, gross losses, persistence, total change and swap change of LULC categories between 1986 and 1995.

	Gross Gain		Gross Loss		Persistence		Total Change		Absolute Net Change		Swap Change	
	Forest	344.9	Agric. Land	621.9	Agric. Land	2552.7	Agric. Land	965.4	Agric. Land	278.4	Forest	689.9
	Agric. Land	343.5	Forest	410.6	Mangrove	481.5	Forest	755.5	Mangrove	177.8	Agric. Land	687.0
1986-1995	Mangrove	331.4	Mangrove	153.5	Water	220.9	Mangrove	484.9	Urban	142.8	Mangrove	307.0
	Urban	206.2	Urban	63.4	Forest	189.7	Urban	269.6	Forest	65.6	Urban	126.8
	Water	79.2	Water	55.7	Urban	71.1	Water	134.9	Water	23.5	Water	111.4
	Total	1305.1	Total	1305.1	Total	3515.9	Total	2610.3	Total	688.1	Total	1922.2

Table 5.15 Ranking of gross gains, gross losses, persistence, total change and swap change of LULC categories between 1995 and 2003.

	Gross Gain		Gross Loss		Persistence		Total Change		Net Change		Swap Change	
	Agric. Land	568.0	Agric. Land	578.7	Agric. Land	2317.5	Agric. Land	1146.7	Urban	272.7	Agric. Land	1135.9
	Urban	387.0	Forest	382.9	Mangrove	481.2	Forest	757.7	Mangrove	190.5	Forest	749.7
1995-2003	Forest	374.8	Mangrove	331.7	Water	202.6	Urban	501.3	Water	63.4	Mangrove	282.3
	Mangrove	141.2	Urban	114.3	Urban	163.0	Mangrove	472.8	Agric. Land	10.7	Urban	228.6
	Water	34.1	Water	97.5	Forest	151.7	Water	131.6	Forest	8.1	Water	68.2
	Total	1505.0	Total	1505.0	Total	3315.9	Total	3010.1	Total	545.4	Total	2464.7

Table 5.16 Ratios of Loss- to-persistence and Gain-to-persistence for LULC Conversions between 1986 and 2003.

	LULC Category	Gain-to-persistence ratio	Loss-to-persistence ratio
	Urban	4.7	0.4
	Forest	1.2	1.5
1986-2003	Agric. Land	0.1	0.3
	Mangrove	0.1	0.2
	Water	0.0	0.2
	Urban	2.9	0.9
	Forest	1.8	2.2
1986-1995	Agric. Land	0.1	0.2
	Mangrove	0.7	0.3
	Water	0.4	0.3
	Urban	2.4	0.7
	Forest	2.5	2.5
1995-2003	Agric. Land	0.3	0.3
	Mangrove	0.3	0.7
	Water	0.2	0.5

5.3.5 Analysis of the Extent of Future Urban LULC changes based on GPH Masterplan.

Figure 5.9 presents the future urban LULC map of Greater Port-Harcourt watershed derived in this study. Recall that the map was derived by overlaying the GPH future Masterplan on the baseline map of this study as discussed in subsection 4.7.1. To derive the 2060 urban LULC map, a supervised classification method was used to classify historical 2003 Landsat imagery, after which the GPH plan layout map was overlaid on the 2003 baseline map. Similarly, the extent of future urban LULC changes was estimated by calculating the area change in km^2 and percentage change between 2003 and 2060.

Visual interpretation.

Figures 5.3 and 5.9 were compared for visual interpretation and the change in the extent of urban area in the later was evident. In other words, the urban area is likely to increase considerably due to the implementation of the plan in future. It also shows that urban growth is expected to occur mainly in a northerly direction; however, to a lesser degree it could also expand towards the easterly and southerly directions (downstream) into areas originally covered by mangrove in 2003.

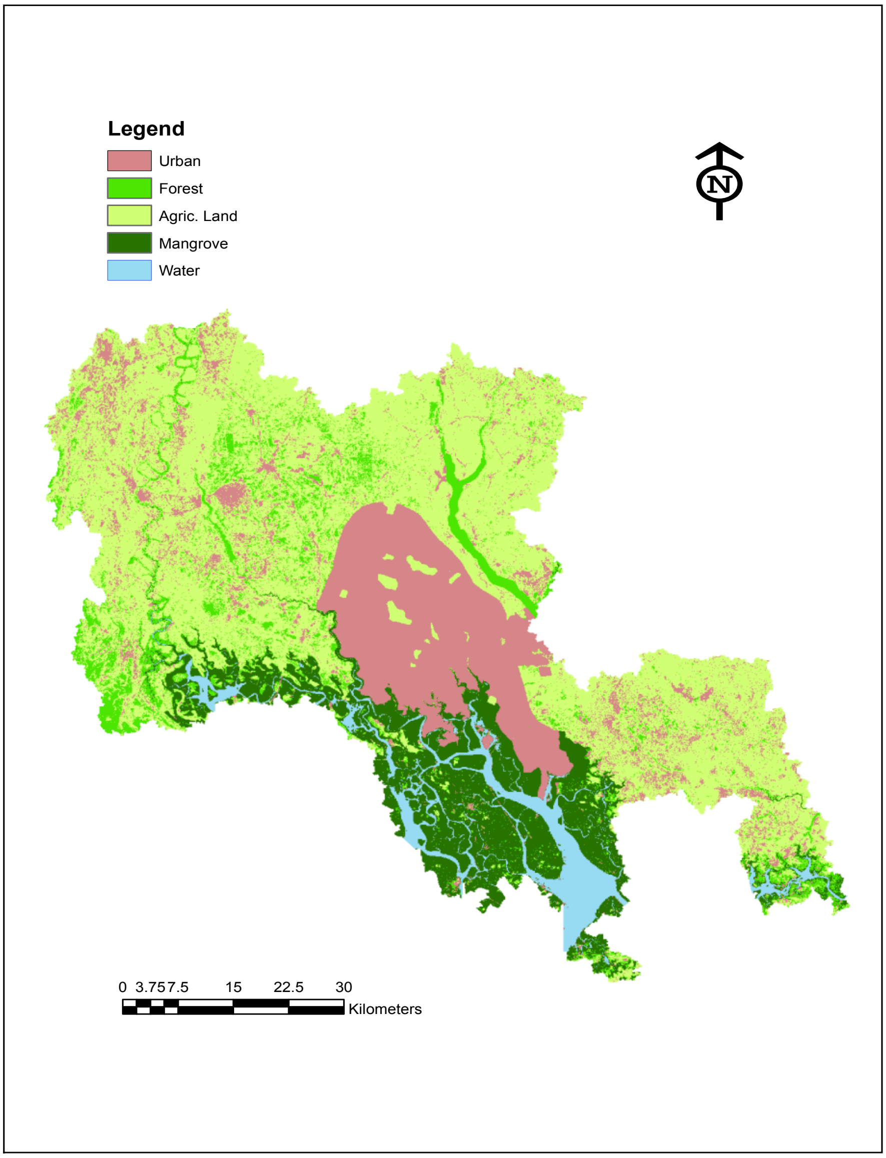

Figure 5.9 Map showing Future (2060) Urban LULC extent in the GPH Watershed. The Projection was based on the GPH Urban Masterplan Layout. LULC Classes include Urban area, Forest, Agricultural Land, Mangrove and Water, (Source: USGS/GPHDA).

Estimated Future Urban Extent.

Table 5.17 presents the result data and addresses the question: *what is the extent of urban LULC change due to the implementation of the plan by 2060*? It presents the proportion (in %), area change and percentage area change by 2060 based on 1986 and 2003 extent. Recall that for the purpose of the study, the study assumes that a change in urban areas would occur due to the plan, while all other categories outside the layout area would largely remain the same.

The result indicates that a significant change in urban LULC is expected by 2060 (Figure 5.10). Based on the difference between 2003 and 2060 maps, the result shows that about 80% (438.2 km^2) increase in urban area is expected by 2060. Figure 5.10 also demonstrates that growth in the proportion of urban area is expected from about 11.4 % in 2003 to about 20.5 % of the watershed in 2060. That is, the urban area is likely to double in proportion. In terms of area in km^2, the bar chart displays a steep rise in urban area from about 550 km^2 in 2003 to about 988 km^2 in 2060. As expected, Figure 5.11 also demonstrates that the proportion of urban area would be greater when referenced to the 1986 area than the 2003 area. From 1986, the proportion of urban area is expected to rise from about 2.8% in 1986 to about 20.5% (600% or seven times growth) in 2060, which is a more significant.

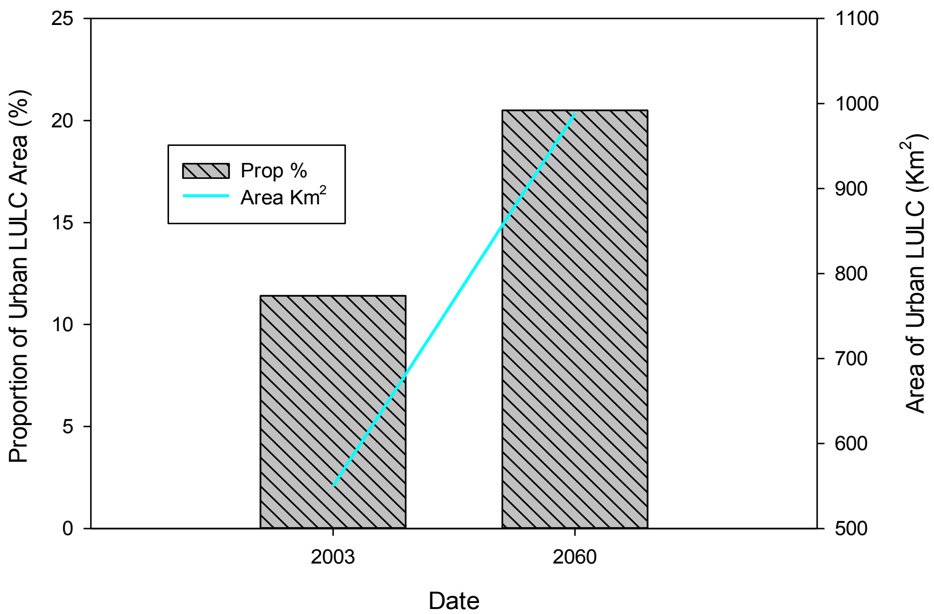

Figure 5.10 Proportion and trend of urban area changes between 2003 and 2060. The bar chart shows the proportion of urban area for the respective dates. The line graph shows the trend and change in urban land-use area.

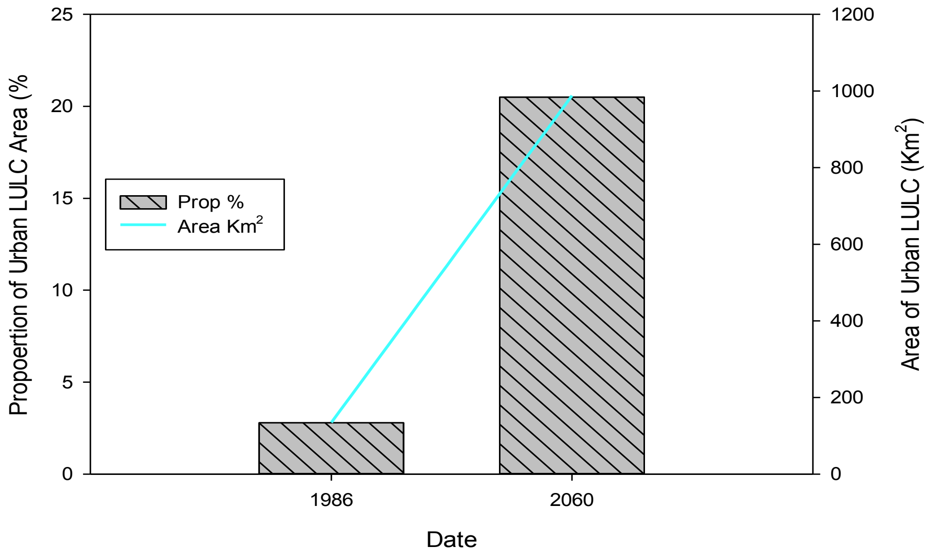

Figure 5.11 Proportion and trend of urban area changes between 1986 and 2060. The bar chart shows the proportion of urban area for the respective dates. The line graph shows the trend and change in urban land-use area.

Table 5.17 Statistics of the Changes in the area of LULCs between 2003 and 2060.

Class Name	2003		2060		Change	
	%	Km^2	%	Km^2	Km^2	%
Urban	11.4	550.0	20.5	988.1	438.2	79.7
Forest	10.9	526.5	9.3	448.3	-78.2	-14.9
Agric. Land	59.9	2885.5	51.8	2497.5	-388.0	-13.5
Mangrove	12.9	622.3	13.5	652.5	30.2	4.8
Water	4.9	236.7	4.9	234.6	-2.1	-0.9
Total		4821.0		4821.0		

Table 5.18 Statistics of the Changes in the area of LULCs between 1986 and 2060.

Class Name	1986		2060		Change	
	%	Km^2	%	Km^2	Km^2	%
Urban	2.8	134.5	20.5	988.1	853.6	634.6
Forest	12.5	600.2	9.3	448.3	-151.9	-125.3
Agric. Land	65.9	3174.6	51.8	2497.5	-677.1	-121.3
Mangrove	13.2	636.4	13.5	652.5	16.1	-97.5
Water	5.7	275.3	4.9	234.6	-40.7	-114.8
Total		4821.0		4821.0		

5.3.6 Comparison of the Historical and Future Extents of Urban area.

Figure 5.12 presents the general trend of changes (historical and future) in spatial extents of urban area estimated for the study area. The analysis shows a progressive growth in urban area from about 134.5 km^2 in 1986, through 277.3 km^2 in 1995, to 550.0 km^2 2003. It further shows that urban area is expected to expand to about 988.1 km^2 by 2060. In other words, the urban area alone within the watershed is expected to double in extent based on the 2003 area. Similarly, growth in the spatial extent corresponds to changes in the proportion of the urban area. In terms of proportion, it indicates that urban LULC grew from approximately 2.8, through 5.8 to about 11.4% historically, and is expected to surge to about 20.5% by 2060. In general, it demonstrates that the urban area could almost double it's 2003 extent and may expand seven times more than its 1986 extent by 2060.

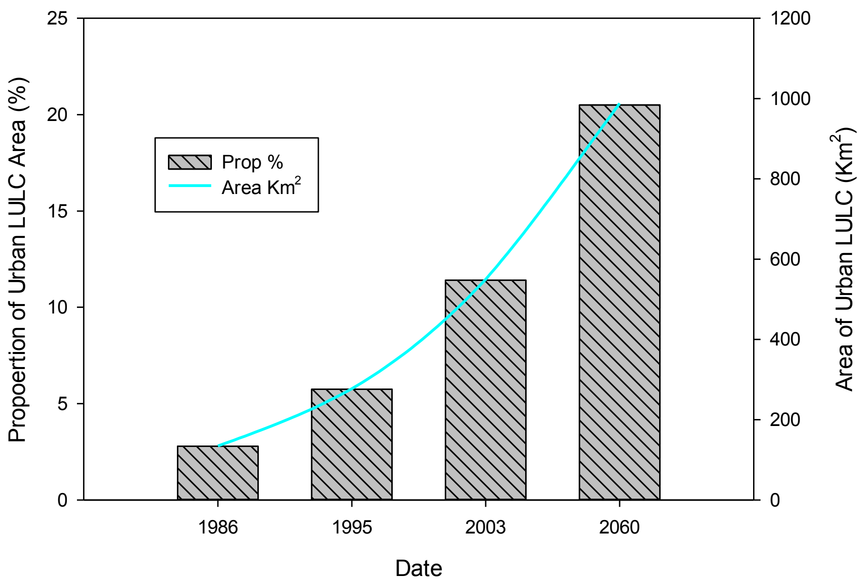

Figure 5.12 Summary of the proportion and trend of urban area changes in historical and future urban scenarios. The bar chart shows the proportion of urban area for the respective dates. The line graph shows the trend and changes to urban land-use area.

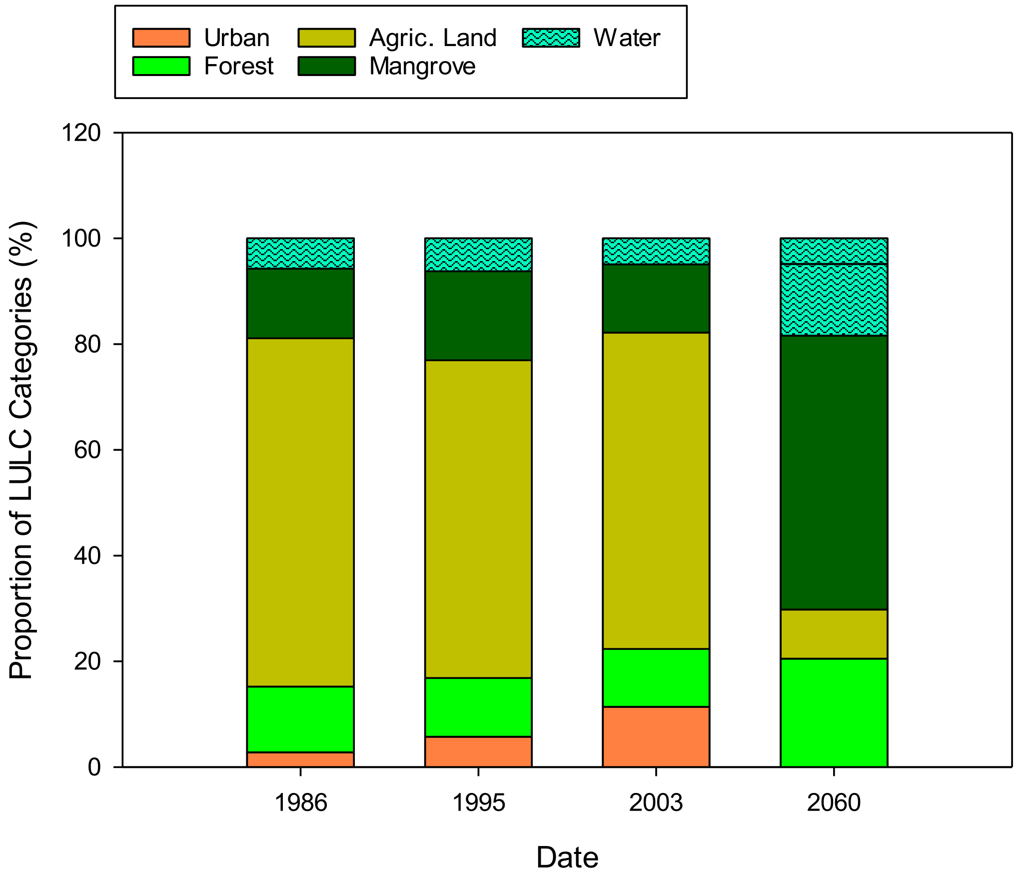

Figure 5.13 Stacked bar chart used for comparing the proportions of all the LULC categories for the historical and 2060 UMP scenarios. Light blue, dark green, pale green, mid-green and orange colours represent water, mangrove, agricultural land, forest and urban areas respectively.

In summary, Figure 5.13 presents the proportional changes of all LULC categories for all historical and future maps analysed. Light blue, dark green, pale green, mid-green and orange colours represent water, mangrove, agricultural land, forest and urban areas respectively. The stacked bar chart clearly shows that the proportion of urban area continued to rise, while the proportion of all other categories decreased at some point or remained fairly the same. Notably, the agricultural land gradually declined from 65.9% in 1986 through 60.08% in 1995 to 59.9% in 2003. It is expected to decrease further to about 51.8% in 2060. Again, the proportion of forest area declined slightly from about 12.5% in 1986 to about 11.1% in 1995 and roughly 10.9% in 2003. It is expected to decrease further to at about 9.3% by 2060. Meanwhile, the area covered by water only declined slightly, but largely remained the same. Apart from the 1995 map, mangrove and water largely remained. In contrast, there was a steady growth in the proportion of urban area, and as stated earlier, significant urban growth is expected by 2060.

5.4 DISCUSSION OF RESULTS.

5.4.1 Extent of historic and future Urban LULC Changes due to Urbanisation.

This subsection discusses the research questions- What was the extent and nature of historical LULC changes? What is the extent of future urban LULC change due to the implementation of the plan by 2060? What are the dominant and key driving forces of land use change in the watershed? Results from this study reveals that a significant change in urban area occurred in the past between 1986 and 2003 and is likely to accelerate until 2060 due to the implementation of the GPH plan. The analysis also reveal that the urban area quadrupled in extent historically, from about 135 km^2 to about 550 km^2 between 1986 and 2003. This suggests that urbanisation was drastic; however, given the limitations in terms of unavailability of appropriate truth data to validate historical changes, there is some uncertainty with result. However, as earlier stated, the classification method applied is reliable and the author is familiar with the landscape. On the other hand, future expansion to 998km^2 means that the old city could nearly double its 2003 urban extent. A significant increase in future urban area means impermeable surfaces are most likely to spread significantly. Again, the result of future changes might have been affected given the assumptions made subsection 4.7.1. The result might also have been affected due to combination of data from different sources and dates as stated in 4.4.1. Moreover, the result section present the trend of change in the landsacpe, and is consistent with previous findings by (Enaruvbe and Ige-Olumide (2014). It is also similar to findings documented for another watershed in Yuan *et al (*2005); Abd El-Kawy *et al (*2011); Du *et al.*, (2012); Hegazy and Kaloop (2015), In contrast, the scale and rate of expansion vary between this and other studies.

Compared to urban expansion documented elsewhere, changes in the urban extent in terms of percentage change was found to be very significant (>100%) in this study. For example, Abd El-Kawy *et al. (*2011) discovered that urban expansion experienced in the desert region of western Nile Delta was very significant by 4934.8% i.e. from 23km^2 in 1984 to 1158Km^2 in 2005. Shalaby and Tateishi, (2007) established that urban area expanded significantly by 666.4% in the north-western coastal zone of Egypt. Likewise, the urban expansion of 309% experienced in the GPH watershed is considered significant. In contrast, Yuan *et al.*, (2005) found that only a 38% (<100%) change occurred in the Minnesota Metropolitan area between 1985 and 2002. Hegazy and Kaloop (2015) concluded that a less significant change (67%) took place between

1984 and 2000 in Mansoura and Talkha cities in Egypt. It indicates that findings in terms extent of urban expansion found in this study is within the range of what was found in other studies.

Urban land is usually of low percentage in many catchments (Chavez and MacKinnon, 1994; Allan, 2004; Manandhar *et al.*, 2010; Kafi *et al.*, 2014). This is consistent with the findings in this study, however 10% percent of urban land was exceeded by 2003 and is expected to reach 20% in 2060. According to Allan (2004), urban land exceeded 5% of catchment area in 29 river basins and exceeded 10% in only 10 of the 150 large basins studied. Even at low percentages, urban land exerts a disproportionate effect on flooding (Leopold, 1968; Allan, 2004), which means a significant change in the extent of urban land in this watershed is expected to cause more dramatic changes in peak discharge. By comparison, findings in this study are also consistent with the results of Allan (2004) who stated that agricultural land occupies the largest proportion of land area in various developed catchments, whereas urban land occupies a much smaller portion.

It is pertinent to highlight that two similar geospatial studies have been carried out for the study area by Mmom and Fred-Nwagwu (2013); Enaruvbe and Ige-Olumide (2014). These studies were mainly municipal scale studies. According to Tellman *et al.* (2016), the strength of the relationship between land use change and flooding among other factors is dependent scale or size of land-use changes. Hence, the previous studies only covered a part of the study area but did not focus on the entire watershed. However, these studies agree that urban expansion occurred in the past, again the degree of change observed differs in all three studies. Enaruvbe and Ige-Olumide (2014) observed that the urban area only experienced 14.6% change between 1986 and 2003 in the part of Port-Harcourt studied. This result was lower than expected given the rate of influx into the cities documented in Obinna *et al.* (2010); Owei *et al.* (2010) and Ede *et al.* (2011). Moreover, Mmom and Fred-Nwagwu (2013) showed that urban area nearly doubles (86%) in extent between 1986 and 2007 which is consistent with findings in this study. Variations in the degree of urban expansion may have resulted due to differences in the total spatial extent and locations considered.

Compared to LULC changes in other watersheds, Agaton *et al.* (2016) showed that built-up areas increased by 100% (13.64 km^2year^{-1}) in the upper Citarum Watershed, West Java Province, Indonesia between 1997 and 2005; while Butt *et al.* (2015) observed that urban area in the Simly watershed, Islamabad (Pakistan) increased by 80% (0.42 km^2year^{-1}) between 1992 and 2012. Moreover, Zhao *et al.* (2016) detected that the urban area increased by only 16%

(15.5 Km^2year^{-1}) in the Weihe River Basin of north-west China. Xiao *et al.* (2006) studied the multi-annual change of urban area in Shijiazhuang City. The study found that urban area increased by 81.5% between 1987 and 2001. The study referred to the growth in the area as 'fast expansion', because urban area grew at a rate of about 5.6 km^2/year. In this study, it was observed that the urban area increased by about 309% at a rate of about 24km^2/year between 1986 and 2003 (bearing in mind there are uncertainties with the result due to data quality issues). However, the result in this study importantly suggests that the GPH watershed experienced a higher rate of urbanisation and that historical urban expansion that took place in this study area can be described as "fast expansion" based on the categorisation in Xiao *et al.* (2006).

Regarding future changes, this study revealed that a significant change in the extent of the urban area is expected by 2060, meaning that the new city's extent is projected to be twice the size of the old city in 2003. Similarly, the predicted increase in the size of urban land is comparable to the trends in other areas documented in other studies. For instance, He *et al.* (2015) projected that urban land is expected to increase from 3635.73 km^2 in 2009 to 4001.00 km^2 in 2015, 4575.44 km^2 in 2020, 5012.76 km^2 in 2025, and 5304.17 km^2 in 2030, which implies a 27.5% increase by 2030. Note that the urban or built-up area is generally considered a parameter for quantifying urban sprawl and can be quantified by measuring the changes in impervious surface (Sudhira *et al.*, 2004; Suriya and Mudgal, 2012; Miller *et al.*, 2014). Hence, Du *et al.* (2012) predicted a rapid rise in impervious surface, from 23% to 31% between 2012 and 2018. This was accompanied by very high losses of paddy field. Similarly, the significant urban changes expected by 2060 means a rapid change in impermeable surfaces.

About the direction of urban change, previous studies have suggested that urban sprawl normally takes place in a radial manner around the city centre or in a linear direction along the highways (Lowry, 1988; Stanilov, 2004; Sudhira *et al.*, 2004; Ngoran and Xue, 2015). Wagner *et al.* (2013) in their work showed that major changes in the urban area occurred on the fringes and in the north-west of the city of Pune, whereas, Xiao *et al.* (2006) found that the main urban LULC changes occurred on the north-west and south-west side of Shijiazhuang city. Consistent with the above study, this study found that urban growth is likely to occur radially around the old city; but changes are mainly expected to occur in the northern and south-eastern axis, i.e. areas dominated by agricultural and forest land and not towards waterbodies or mangrove. This suggests that the direction of expansion in the watershed is partly shaped by the availability of suitable land and the physiography of the area. Moreover, based on the GPH map, much of the growth is expected to be an 'out-extension' type of growth. However, to a lesser degree, 'in-filling' growth is also projected to occur at the fringe of the old or already built-up areas.

Trend of Land use/Land cover changes.

Beside the alarming rate of urban expansion observed in the study area, the general trend of other LULC changes is also a concern. The general trend in Figure 5.13 indicates a continuous rise in the urban area accompanied by a continuous decline in agricultural land and forest. However, there are also wide-ranging results in terms of non-urban changes; Weng (2002); Sudhira *et al.* (2004); Yuan *et al.* (2005); Xiao *et al.* (2006); Dewan and Yamaguchi (2009); Abd El-Kawy *et al.* (2011); Du *et al.* (2012); Butt *et al.* (2015); He *et al.* (2015); Hegazy and Kaloop (2015); Zhao *et al.* (2016) and Agaton *et al.* (2016). Butt *et al.* (2015) concluded that there was a major decline in vegetation and water classes, accompanied by an increase in agricultural land and bare soil between 1992 and 2012. Du *et al.* (2012) established that there was a substantial decrease in paddy field, while woodland, water and dry land declined slightly. Similarly, Du *et al.* (2012) predicted a progressive increase in urban area in the future. This shows that the finding in terms of the trend of urban changes in this study is similar to findings in other studies compared in this study; however, the conclusion for the trend of non-urban changes in this study differ with findings in other studies.

The result in this study support claims in previous local studies that suggest that urbanisation has been the main type of human-induced land degradation in the area; however, there are also discrepancies in terms of non-urban changes in the area. For example, Enaruvbe and Ige-Olumide (2014) agree that there was a substantial loss of agricultural land, but the study found no change in mangrove class type. Moreover, the study also claim that there was an increase in water and natural forest. However, this study argues that there was a considerable loss of forest partly due to the high rate of urban expansion based on the analysis. This finding is consistent with other local studies including NDDC (2006); Daramola and Ibem 92010) Owei *et al.*, (2010) Onojeghuo and Blackburn (2011); Mfon *et al.*, (2014) and Wizor, (2014). Daramola and Ibem (2010) suggested that deforestation in the area resulted mainly from construction projects and subsistence activities e.g. farming and logging. Importantly, there has been no evidence of future urban changes in this watershed in previous studies, but based on results in Table 5.17 and 5.18, this study projects that urban area could expand to about 998 km^2 in 2060, which is about seven and two times its extent in 1986 and 2003 respectively. Keep in mind that there are some uncertainties with the results due to combination of multi-source data and assumptions made in the study.

5.4.2 The Nature of Historic Urban LULC Changes in GPH Watershed.

The Nature of Land-use/Land-cover Change.

Apart from the extent and trend of change, this subsection further addresses the nature of changes based on the cross-tabulation (Tables 5.8-5.10). Analysis of the nature of change was valuable in understanding not just the important shifts, but also the process of change and tendencies of the land-use categories to change within the watershed. In other words, the queries are, which land use class is changing to the other? What type of change did the most prominent shift undergo? In addition, what is their tendency to expand or contract?

Generally, this study found that three-quarters of the entire watershed persisted to change, whereas one-quarter of the watershed transitioned from one LULC category to another within the 17-year period. The urban area experienced the grossest gain, while agricultural land experienced the most loss. Also, 70% of the area that persisted was composed of agricultural land. It then means that the dominant changes included urban expansion and loss of agricultural land. In terms of the total changed area, the landscape experienced more swap change than net change. In other words, changes in the watershed were mainly due to changes in location than actual change in quantity. Therefore, urban expansion and loss of agricultural land are the most important changes to be managed in the watershed, and a substantial part of the watershed landscape transitioned, but the transition was more of a swap change than a net change. It pertinent to state that there are some uncertainties about this result due to possible errors from a number of sources. In this case, the percentage of swap changes may have been affected due to error from classification. However, the result was acceptable based on: similarity in the trend of changes when compared with prior studies, reliability of method of classification applied, and knowledge the landscape to the author.

Based on analysis of prominent inter-categorical shifts between 1986 and 2003, this study agrees that urbanisation has been the main driving force of land use change in the watershed. This is because urban land experienced the grossest gain and the grossest loss resulting in a high net gain, unlike agricultural land and forest. Gross and net gain are important measures of expansion (Lu *et al.*, 2004; Manandhar *et al.*, 2010). %. Again bearing in mind there are some uncertainties due data quality issues, this study found that the urban land experienced the highest gross gain (9% of the watershed) and the highest net gain of 8.6 Therefore, urban land use change was the most dynamic in terms of gross gain and net change within the period (Tables 5.8), unlike other categories. In terms of the process or type of change, urban land exhibited more of a net type of change than swap type of change compared to all other classes that exhibited a swap type of change. Based on the explanation by Pontius *et al.* (2004), it means that changes in urban area were more of a change in quantity than location, indicating that there have been an actual change in magnitude that could compound flood risk. Moreover, compared to other classes, urban land also exhibited the highest gain-to-persistence ratio (4.6), greater than one (>1). This means urban land exhibited a very strong tendency to expand rather than persist. Based on this evidence, I concluded that urbanisation had been the main driving force of land use change in the watershed.

The study also found that urban growth in the city resulted chiefly at the expense of agricultural land, and to a lesser degree, forest, while the urban transition from mangrove and water were negligible. Since about 93% of the transition to urban land was derived from agricultural land, it implies that there has been a substantial encroachment of planned and unplanned settlements into agricultural land. This trend differ in studies. For instance, Manandhar *et al.* (2010) and Liu *et al.* (2015) found that urban land gained 41% and 43% of agricultural/shrub land respectively, while Nkeki (2016) found that urban land only gained 25% of agricultural land, which was the lowest. In contrast, conversion of agricultural land to urban area in this study was reasonably higher than similar conversion in the above studies. This trend observed agrees with studies by Lambin *et al.* (2001) who found that urbanisation in developing countries often dominate all other uses of land next to the city, including important arable land. The high net gain of the urban area, high net loss of agricultural land and the increasing extent of the urban area found in this study supports the narrative about decline of agricultural practices in Nigeria. According to Olajide *et al.* (2012), agriculture was the dominant factor in the region's economic development, i.e. even during the early stage of industrialisation. However, over time industrial activities accompanied by the high rate of urbanisation superseded agricultural activities as the most influential economic force in the region.

Two important non-urban transitions were found in this study. These were the shift from agricultural land to forest and the shift from forest to agricultural land suggesting that a substantial exchange occurred. Despite the significant loss of agricultural land to urban area, this study found that there was a considerable exchange between agricultural land and forest, although more forest was lost to agriculture than the opposite. For instance, about 321km^2 of forest was lost to agricultural land, at the same time approximately 230km^2 of agricultural land was lost to forest. However, agricultural land alone lost more (654km^2) than it gained (365km^2). Note: take into consideration that there are some uncertainties with these values due to possible errors from a number of sources stated in subsection 4.4.1. For example, in this case, misclassification may affected the accuracy of the result, nonetheless, due to method of classification and author's knowledge of the study area, the results were deemed reliable. Importantly, this result helps to explain why swap-type changes dominated the landscape more than net-type change. In contrast to urban land-use changes, agricultural land is the most dynamic in terms of total change, swap change and persistence, indicating that there was considerable persistence and shift in both positive and negative directions. It also shows that changes in agricultural land were largely due to change in location and to a lesser degree, changes in quantity. In brief, the loss of agricultural land was another prominent land-use change. For agricultural land, substantial amount changed location but the most part persisted.

About forest and other LULCs, analysis of the results revealed that more than about 50% of the forestland were converted from agricultural land. Forest conversion was a swap of change, which helps to establish the fact that a substantial exchange between forest and agriculture took place (i.e. between 1986 and 2003). Between 1986 and 2003, result show only about 13km^2 (2%) of forestland was converted to urban area, suggesting that some deforestation took place due to urban expansion. However, the conversion of forest to the agricultural area was relatively higher than conversion of forest to urban. The indication is that the loss of forest was mostly affected by agricultural practice rather than urbanisation. Perhaps this implies that people found agricultural land more suitable than forest. Forestland experienced a declining net loss rate from -7.2 km^2 y^{-1} in 1986-1995 to -1.0 km^2 y^{-1} 1995-2003 that is much lower than the rate estimated by Li *et al.* (2016). Mangrove and water eventually declined, but transitions to and from these categories were negligible as expected. For instance, only about 2% and 0.7% of mangrove and water were converted to urban areas respectively. Forest also showed a loss-to and-gain-to-persistence ratio greater than one (>1) indicating that forest has a higher tendency to expand than persisting; and the highest tendency to contract than persisting at the same time. Deforestation is another important process of land use change; however, a large fraction of the forest was exchanged with agricultural land in the watershed.

This study also found that urban areas showed a higher tendency to expand rather than persist among all LULCs. Although the underlying cause of urban growth was not investigated in this study, globally, prior studies suggest that high population growth is the main reason for urbanisation (Foley *et al.*, 2005; Sajjad and Iqbal, 2012). Locally, the city is known to attract significant rural population attributable to socio-economic factors (Ede *et al.*, 2011; Mmom and Fred-Nwagwu, 2013; Elenwo and Efe, 2014; Wizor, 2014). The study further reveals that the direction of growth was mainly towards the northern axis, indicating that increased impermeable cover is expected upstream. Research has shown that increased development upstream affects downstream flooding (Heggen *et al.*, 1996; Parker, 2000a). Northerly movement of urban land means that developments are expected to encroach on to predominantly agricultural land, implying that agricultural land is deemed more suitable than forest for urban development in the watershed.

5.4.3 Implications for the GPH watershed.

The GPH watershed is a sensitive tropical wetland characterised by a dense network of rivers (Barbier, 1994; Abam, 2001; Munji *et al.*, 2013). Land-use change is a major factor that affects the hydrological functioning of watersheds. Afforestation and deforestation, the intensification of agriculture, the drainage of wetlands, road construction and urbanisation are the widely recognised changes in land use that alter hydrology (Hollis, 1975; Parker, 2000b; De Roo *et al.*, 2001). However, this study reveals that urbanisation and deforestation are critical processes that have implications for a number of subbasins.

Rapid urbanisation is usually accompanied by an increase in impermeable surfaces which can compound flood risk in the area by reducing infiltration. When a catchment increases its percentage of impervious cover from 0-60 % of its area due to urban growth, flow can be increased two to five times of its pre-urbanisation state (Leopold, 1968), depending on the geometry of impervious surface and watershed size (Tellman *et al.,* 2016). Hollis (1975) demonstrated that 30% of impermeable surface might double the size of floods with a 100yr return period in small watersheds, and small floods might be increased by ten times due to urbanisation.

This research establishes that urbanisation is the main driving force, although the urban area is usually a low percentage. Even little changes in the percentage of urban can cause dramatic effects of flooding (Leopold, 1968; Hollis, 1975; Du *et al.*, 2012). Therefore, the changes in the extent and type of land-use change can have severe effects on floods. Nirupama and Simonovic (2006) reported that urbanisation increased the risk of flooding considerably in the watershed of the Upper Thames River, in the province of Ontario, Canada. In 2012, Port-Harcourt among other areas witnessed a disasterous flood event that was attributed to intense precipitation and developments upstream (GFDRR, 2013). The impact of the floods was reportedly very severe in Port-Harcourt, which left 363 people dead, 5,851 injured, 3,891,314 affected, and 3,871,530 displaced. Therefore, increased urbanisation may amplify flood risk.

Deforestation can also have severe implications for flooding because of reduced interception losses; however, the precise effect in large watersheds varies for different watersheds (De Roo *et al.*, 2001; Bruijnzeel, 2004; Bathurst *et al.*, 2011). From the analysis, about 73km^2 of the forest was eventually lost between 1986 and 2003. Recall, the large fraction of forest land-use change was more a swap type of change rather than a change in a quantity, which implies forest disturbance. Forest disturbance can accelerate the rate that precipitation becomes streamflow depending on the catchment and storm size (Jones *et al.*, 2009). In this case, the cutting of trees due to urbanisation and replacement of forestland by agricultural land can temporarily affect the volume and quality of water flowing downstream. Besides, some local areas may experience increased streamflow and overland flow. The impact of deforestation on flooding is more obvious in small basins than large watersheds. Therefore there is a need to investigate forest effects on flow in the GPH watershed, and this should be a concern for planners. According to Tellman *et al.,* (2016), the impact of forest also depends on what the forest transitions into. In this case, forest was majorly converted to agricultural land and to a lesser degree urban land. Both types of changes can degrade water quality and increase flood risk.

Land use change associated with loss of agricultural land is among the dominant changes observed in this study area. Agricultural land experienced the highest net loss; hence, a significant amount was converted into urban area. Although the impacts of such conversion vary at watershed scale, the vulnerability to flooding may increase locally due to changes in soil infiltration capacity and increased runoff. Similarly, the conversion of mangrove (wetland) to urban area is also a concern. For instance, Varnell *et al.* (2003) revealed that at least 35% of mangrove have been lost in the global environment. Besides, for shoreline stabilisation, mangroves play a crucial role in complementing other flood defence strategies. For instance, mangroves could protect people by reducing storm surge for every kilometre of mangrove that the storm surge passes through. Findings in this study suggest that at least 1.88% of mangrove forest will likely be lost by 2060, at a rate of 0.156% per annum in the watershed, which contributes to the global decline. For the locals, it means that protection from coastal flooding may also continue to reduce.

Lastly, urbanisation and deforestation could have severe ecological implications. For example, increasing urban land within the watershed has been linked with substantial changes in biological assemblages in other areas (Allan, 2004). Riparian zones serve as ecological corridors for migrant species, but can also help to reduce runoff in cities (Nagasaka and Nakamura, 1999; Moradkhani *et al.*, 2010). Urbanisation identified as the dominant process in this study may enhance vegetation clearing and reduction of riparian zones, and as such may increase stream temperature, plant growth and light penetration. Extreme or high flows due to urbanisation can increase erosion rates as well as habitat degradation. Such flows could also eliminate taxa if flood events occur during sensitive life stages (Allan, 2004). Finally, sediment input resulting from urbanisation might cause a reduction in the channel and habitat structure (Allan, 2004).

5.5 CONCLUSION.

This chapter provided the analysis of historical and future LULC dynamics in the GPH watershed. First, this study concludes that urbanisation has been the driving force of land use change in the study area; and this trend is likely to continue until 2060 due to the implementation of the GPH Masterplan. Historically, the result show that urban land quadrupled in extent from about 135 km^2 to about 550 km^2 between 1986 and 2003, which is a 309% change. In future, the study shows the urban area could nearly double its 2003 extent. Note: bear in mind that there are some uncertainties with the exact percentage of change due to possible errors from different sources and assumptions made in the study. While no result is perfect, this result was deemed acceptable because of the reliability of the methods applied and because the trend is consistent with results in prior published studies. The important message is that urban expansion was rapid and could rapidly increase by 2060 due to the GPH development. On the other hand, the nature of change observed includes high net and gross gain of urban land accompanied by the decline in all other LULCs. Based on the analysis, this study concludes that the loss of agricultural land and deforestation also accompany urbanisation. The study also reveals that agricultural land was the dominant land use, but may decline significantly due to future urbanisation which may amplify peak discharge.

On the nature of change, this study found that about one-quarter of the watershed transitioned from one LULC category to another within the 17-year period studied, while three-quarter of the landscape persisted. Importantly, the shift to urban area was the most dynamic in terms of gross gain and net gain. Importantly, about 93.3% of all LULC conversions to urban land resulted from agricultural land. In contrast, the transition from other LULC classes to urban areas was very low. Hence, this study concludes that urbanisation occurred mainly at the expense of agricultural land. Although previous studies have investigated the nature of change in the area, the LULC changes covering the entire watershed were not investigated. Moreover, there has been little or no evidence on the process of change within the watershed, which is critical for understanding of actual change that could affect flooding. This study has shed light in that area by showing that urban areas experienced more of a net-type of change than a swap-type of change unlike all other classes. This implies that urban land-use changes were more of a change in quantity than in location.

In contrast, agricultural land was the most dynamic in terms of gross loss, total change, swap change and persistence. However, this study concludes that changes in agricultural land were more of a swap rather than a net type of change, which is comparable to other non-urban transitions. This finding reinforces the fact that urbanisation has been the main driving force of land use change in the watershed. Urban areas also showed a very high gain-to-persistence ratio, meaning it had a higher tendency to expand. In contrast, agricultural land showed a high tendency to contract. Finally, this study demonstrates that analysing the extent and nature of changes without understanding the process of change might underestimate the total change. That is, analysing the LULC impacts based on traditional transition matrices alone might be misleading because the total change might be underestimated.

Chapter 6. Effect of Urbanisation and Climate Change on Urban hydrology in the Greater Port-Harcourt Watershed.

6.1 INTRODUCTION.

As stated in the literature review chapter, the impact of urbanisation and climate change on flooding in small catchments is more predictable and well understood owing to improved understanding of hillslope hydrology. The GPH watershed is a large watershed of over $4000km^2$. The impact of urbanisation on flooding is more complex and difficult to predict in such large catchments. On this note, the runoff dynamics and the impact of urbanisation on flooding in the GPH watershed requires detailed investigation. Flooding is a product of physical (rainfall) and human disturbance (e.g. urbanisation). Land use and other human activities alter hydrologic processes in watersheds by modifying how rainfall is stored, and how water runs off the land surface into streams (Hollis, 1974; Du *et al.*, 2012). Among the land-use change types, it is believed that urbanisation generates the most dramatic effect on catchment hydrology, which is often as a result of increased runoff and runoff volume as well as reduced infiltration rates, base flow, and time to peak.

It is also widely believed that the effects of urbanisation depend on the amount of rainfall and watershed characteristics. This includes the rainfall distribution, intensity and duration as well as location of development, basin shape, soil nature and depth, geologic structure, topography, size, area, slope and channel characteristics (Brooks *et al.*, 1991). Similarly, the effects of forest on flooding depend on rainfall and watershed characteristics. While the effects of urbanisation on large watershed in other areas have been studied extensively, there is little or no evidence of the effects of future climate and land-use changes on the GPH catchment.

The objectives of this chapter are three twofold. First, to assess the historical and future effects of rainfall and land-use changes on runoff. Second, to assess the effects of alternative location to Phase-1 development on runoff in sub-basins. Third, to understand the extent to which afforestation could reduce runoff in the GPH watershed. Before the main chapter objectives were dealt with, the resultant changes in percentage of impervious area (PctImp) and curve number (CN) were determined. Section 6.2 briefly iterates the material and method applied in the chapter (see Chapter 4 for a detailed description of the methodology). Section 6.3 presents the result and data analysis, while section 6.4 discusses the result and analysis. Finally, Section 6.5 presents the conclusion.

6.2 MATERIALS AND METHODS.

In this study, runoff from the landscape was modelled using HEC-HMS, as detailed in chapter 4. However, prior to using the HEC-HMS model, a 90m x 90m resolution Digital Elevation Model (DEM) was used to delineate the watershed and simulate the stream network with HEC-GeoHMS. DEM data used as input was acquired from the Shuttle Radar Topography Mission (SRTM). Other inputs to the model included: soil data (from the FAQ), historic and future land-use data (from the USGS and GPHDA plan), and rainfall data (from NIMET). Appendix 6.1 to 6.5 presents all historical and future land-use scenario maps used as inputs. HEC-HMS developed by the USACE's Hydrologic Engineering Centre (HEC) uses separate sub-models to represent each component of the runoff process. The HEC-HMS software combines models that estimate: loss (runoff volume), transformation (discharge runoff), base flow and channel routing respectively (Feldman, 2000; USACE, 2009, 2013). In each model run, the Basin model, the Precipitation model, and the Control model were coupled to generate result. The Basin model consisted of the basin elements, connectivity data and routing parameters and these were used to model the physical processes in the watershed. The Precipitation model contained the meteorological data for the model, while the Control model was used to manage the time series data for the model. Statistical analysis, including one-way ANOVA and regression analysis were used for data analysis, to assess changes between groups and relationships between variables. Finally, the flow data was used as input into the HEC-RAS model.

6.3 RESULTS.

6.3.1 Model performance.

Tables 6.1 and 6.2 present results of error functions employed for the model validation. Three statistical measures were used, consisting of; mean absolute error (MAE), root mean square error (RMSE), and relative percentage error (RPE). For validating the model, four annual storm events were selected. The selected events correspond with the time periods of the observed annual peak flow data found for Imo River (see subsection 4.9.9 for more details). Generally, the model validation results demonstrated a reasonable performance. That is, the model estimates were close to observed values in the work of Okoro and Uzoukwu (2013). For example, the relative errors for all events based on the observed values were 0.05, 0.40, 0.14 and 0.09m$^{3/}$s, which is reasonable. Compared to other studies, the MAE for peak discharge was 39.8 m^3/s and is reasonable when compared to MAE value observed in Knebl *et al.* (2005). Similarly, RMSE estimated as 45.48m^3/s suggests a reasonable performance when compared to RMSE values recorded in Roy and Mistri (2013). Given the limited data and the performance of the model, model prediction was deemed reliable for modelling other historical and future hydrologic changes.

Table 6.1 Comparison of error functions for annual peak flows for the Imo River outlet between 1985 and 1988.

Year	Observed Qp (m^3/s)	Estimated Qp (m^3/s)	Absolute Error (AE)	Squared Error (SE)	Relative Error (RE)	Relative Percentage Error (RPE)
1985	286.1	273.1	13	169	0.05	4.54
1986	200	279.6	79.6	6336.16	0.40	39.80
1987	223.2	255.3	32.1	1030.41	0.14	14.38
1988	307.8	280.6	27.2	739.84	0.09	8.84

Table 6.2 Summary of model performance of estimated annual peak flows for Imo River outlet between 1985 and 1988.

Performance criteria	Values
MAE	37.98
RMSE	45.49
MRPE	16.89%

6.3.2 Urban development and resultant changes in impervious surface area.

To examine the historical and future changes in impervious surface in the GPH watershed, Tables 6.3 and 6.4 present results in terms of total impervious surface area and the percentage of impervious surface area (PctImp) in the watershed. Appendix 6.6 presents derived PctImp values used as model inputs. The total impervious surface area was calculated by multiplying the impervious surface coefficients by the shape area based on the respective LULC grid codes in the attribute table. The percentage of impervious surface area for each date was determined by dividing the total impervious surface area by the watershed area and multiplying by 100.

Table 6.3 Table of all urban scenarios showing changes in Total impervious surface area as well as the percentage of the impervious surface area of the watershed. PctImp denotes the percentage of impervious surface. UMP means the urban Masterplan scenario. UUMP means an urban Masterplan + urban sprawl. NF means No forest. LAF means low afforestation and HAF means high afforestation.

Years/ Urban Land-use scenario	Urban Area (km^2)	Total Imp. Surf Area (km^2)	Percentage of Imp Surface Area (%)
1986	134.5	363.2	7.5
1995	277.3	485.9	10.0
2003	549.9	620.2	12.9
UMP	988.1	803.1	16.7
UUMP	1238.5	914.3	18.9
NF	1238.5	941.4	19.5
LAF	1238.5	919.9	19.2
HAF	1238.5	931.6	19.3

Historically, the watershed experienced a significant increase (about 70%) in paved surfaces between 1986 and 2003. This change was from about 363 km^2 in 1986 (covering 7.5% of the entire watershed) to approximately 620km^2 in 2003 (covering about 12.9% of the entire watershed). As expected, the bar chart below (Figure 6.1) shows an upward trend indicating that the total impervious surface area increased as the spatial extent of the urban area increased. Table 6.4 shows that there is a significant differences in PctImp between 1986 and 2003 as well as between 1995 and 2003; however, it also showed no significant difference in PctImp between 1986 and 1995 (Table 6.4).

Again, the extent of impervious surface is greater than the extent of urban area across all scenarios analysed. The result in Appendix 6.6 indicates that sub-basins in the Port-Harcourt-Bonny basin experienced the most dramatic increase in impervious surface. In terms of future changes, results in Table 6.3 and Figure 6.2 indicate that impervious surface is expected to increase significantly by 2060 based on the urban Masterplan.

Table 6.4 Analysis of Variance performed for Percentage of Impervious Surface between historic scenarios for the GPH Watershed.

Comparison	P	P<0.050
PctImp-2003 vs PctImp-1986	<0.001	Yes
PctImp-2003 vs PctImp-1995	<0.001	Yes
PctImp-1995 vs PctImp-1986	0.100	No

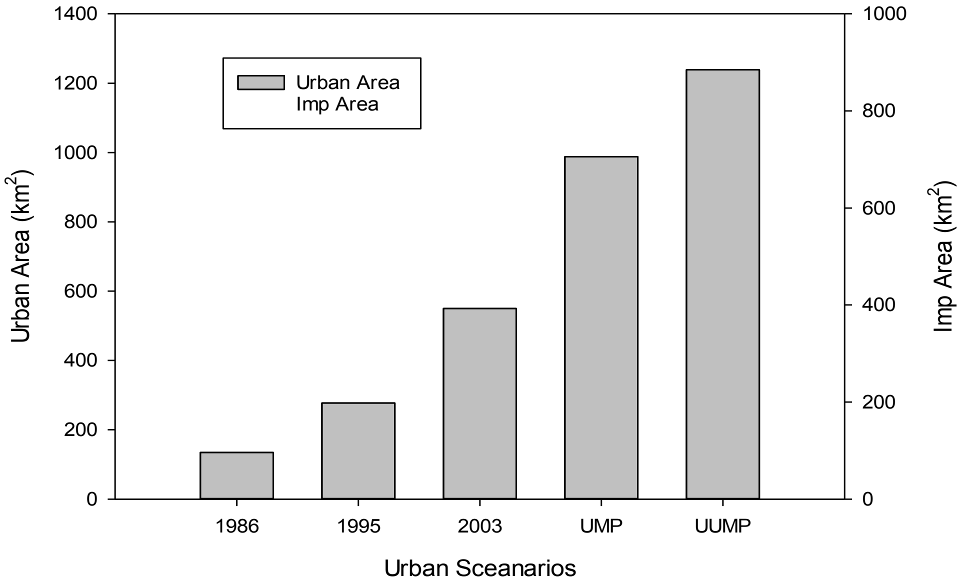

Figure 6.1 Stacked bar chart showing changes in urban area with resultant increase in the percentage of impervious surface estimated for the historical and future urban scenarios.

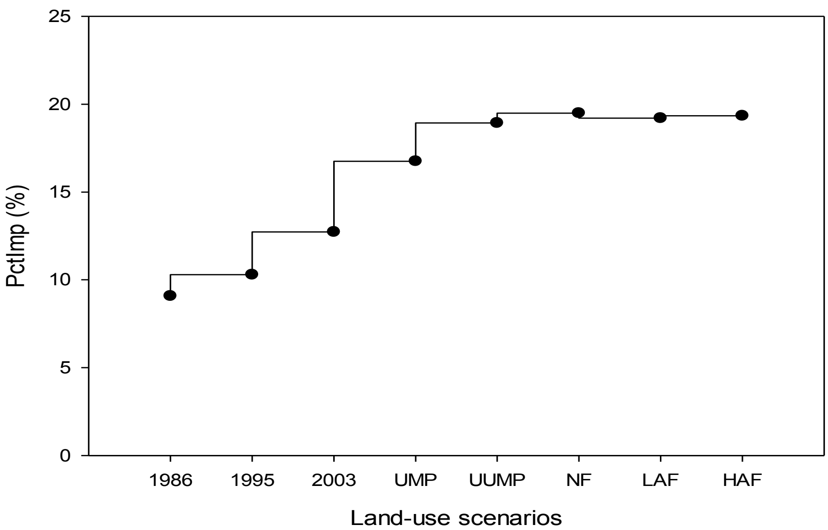

Figure 6.2 Horizontal step plot-showing changes in the percentage of impervious surface in the watershed for the different land-use scenarios. UMP=Urban Masterplan, UMUMP=Urban sprawl +Urban masterplan scenario, NF=No Forest, LAF=Low afforestation and HAF=High afforestation scenario.

6.3.3 Urban development and Resultant changes in Curve number.

To estimate the historical and potential changes in curve number in the watershed, Table 6.5 presents estimates of average and maximum CN in the watershed. The NRCS-CN is an index that represents the runoff potential of a sub-basin. It was determined by integrating land-use and soil data as explained in the methodology chapter (chapter four).

Table 6.5 Table showing changes in Curve number (CN) for all scenarios, including the maximum CN estimated in each scenario. Results are based on data in Appendix 6.7.

Urban Land-use scenarios	Urban Area (km^2)	Total Imp Surf Area (km^2)	Mean CN	Max CN	Std. Dev CN	Std. Error CN	C.I. of CN
1986	134.5	363.2	76.7	98.8	10.7	1.72	3.47
1995	277.3	485.9	78.2	98.9	10.9	1.75	3.54
2003	549.9	620.2	78.3	99.8	9.9	1.59	3.22
UMP	988.1	803.1	80.3	99.8	9.4	1.50	3.04
UUMP	1238.5	914.3	80.3	99.7	9.3	1.49	3.02
NF	1238.5	941.4	81.4	99.8	8.8	1.40	2.84
LAF	1238.5	919.9	80.6	99.7	9.2	1.47	2.98
HAF	1238.5	931.6	81.1	99.7	8.2	1.31	2.66

Note: CN means curve number

Changes in CN are similar to changes in the percentage of impervious surface. However, the difference in mean CN between the historical dates was not statistically significant. The horizontal step plot in Figure 6.3 clearly shows that the historic CN values for the watershed increased progressively from about 76.7 in 1986, through 78.2 in 1995 to about 78.3. Moreover, Table 6.5 also shows that the mean CN associated with urban Masterplan increased to about 80.3. Again, the differences between the historical and future urban scenarios are not significant. Generally, the difference in CN between the 2003 scenario and all future urban and afforestation scenarios analysed are not pronounced. Figure 6.4 show corresponding changes with CN impervious surface and urban area.

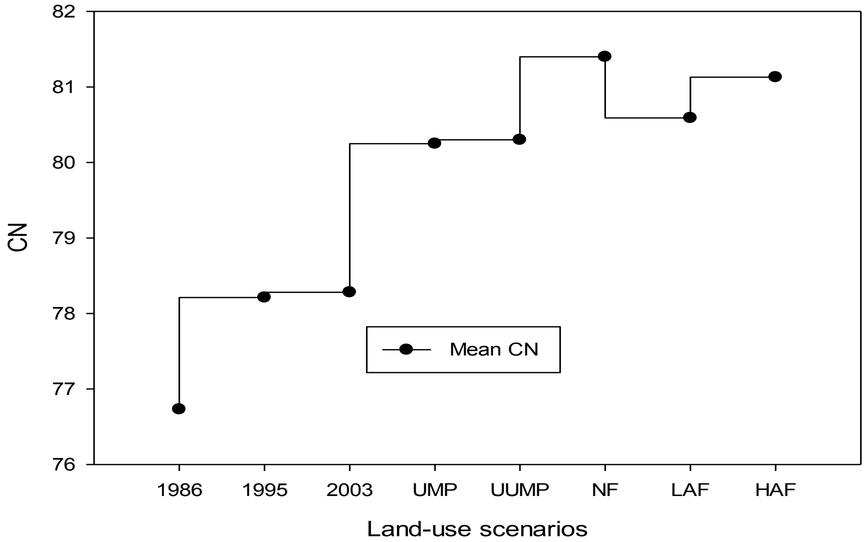

Figure 6.3 Horizontal step plot showing changes in mean CN for all scenarios. It shows an increase in CN between 1986 and 2003. Plot is based on data in Appendix 6.7.

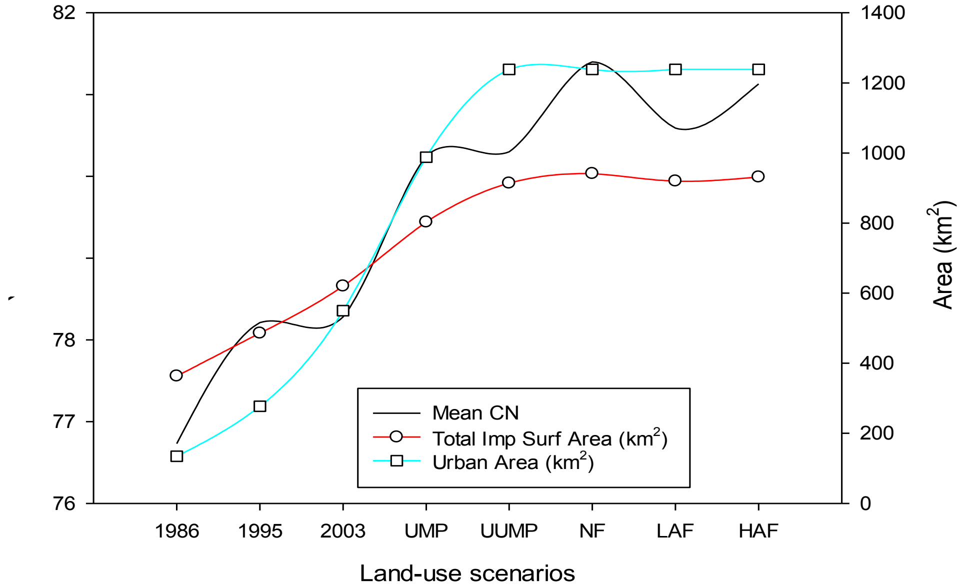

Figure 6.4 Line graph showing similar trend of changes in CN, impervious surface and urban area in the watershed for all scenarios. It generally shows a drastic rise in urban area from 1986 to 2060. Percentage of impervious surface is approximately the same across all future scenarios.

6.3.4 Effects of Urbanisation on Watershed Hydrology.

Historical Effects on Runoff due to changes in urban area and storm size.

In order to analyse the historical impact of urbanisation and rainfall on runoff, this study applied the rainfall-runoff modelling technique (section 4.9 in chapter four for further details). Table 6.6 present results of changes in peak discharge between 1986, 1995 and 2003. But first, the table also shows that the watershed experienced significant increase (about 300%) in urban area between 1986 and 2003, corresponding with a significant rise (about 70%) in the percentage of impervious surface. Historically, the annual maximum daily rainfall (AMDR) increased from 104 to 173mm. Note Scenario maps generated in the study are found from Appendix 6.1 to 6.6.

Consequently, Table 6.6 show a significant increase in annual maximum peak discharge in the watershed, between 1986 and 2003. It increased significantly by 68% between 1986 and 2003 (from about 207 m^3/s to about 347 m^3/s). Meanwhile, the pre - urbanisation ratio in peak discharge amplified from about 1.2 by 1995 to about 1.7 by 2003. These results generally indicate that maximum peak discharge progressively increased as urban area and storm size increased between 1986 and 2003. Data for peak flow responses to urbanisation and afforestation can be found in Appendix 6.8, 6.9 6.10 and 6.11.

Table 6.6 Peak flow response to different urbanisation and rainfall condition. QP= peak discharge, %Δ= Percentage change from 1986, Pre-urbanisation ratio = QP of historical dates/QP of 1986. Peak flow results are based on data in Appendix 6.8.

Time period	Rainfall Depth (mm)	Urban Area (km^2)	Percentage of watershed paved (%)	Annual Maximum Peak Discharge - Q_P (m3/s)	%Δ in Q_P	Pre-urbanisation Q_P Ratio
1986	104.3	135	7.5	206.8		
1995	126.7	277	10.0	254.1	23.0	1.22
2003	173.4	550	12.9	347.8	68.0	1.68

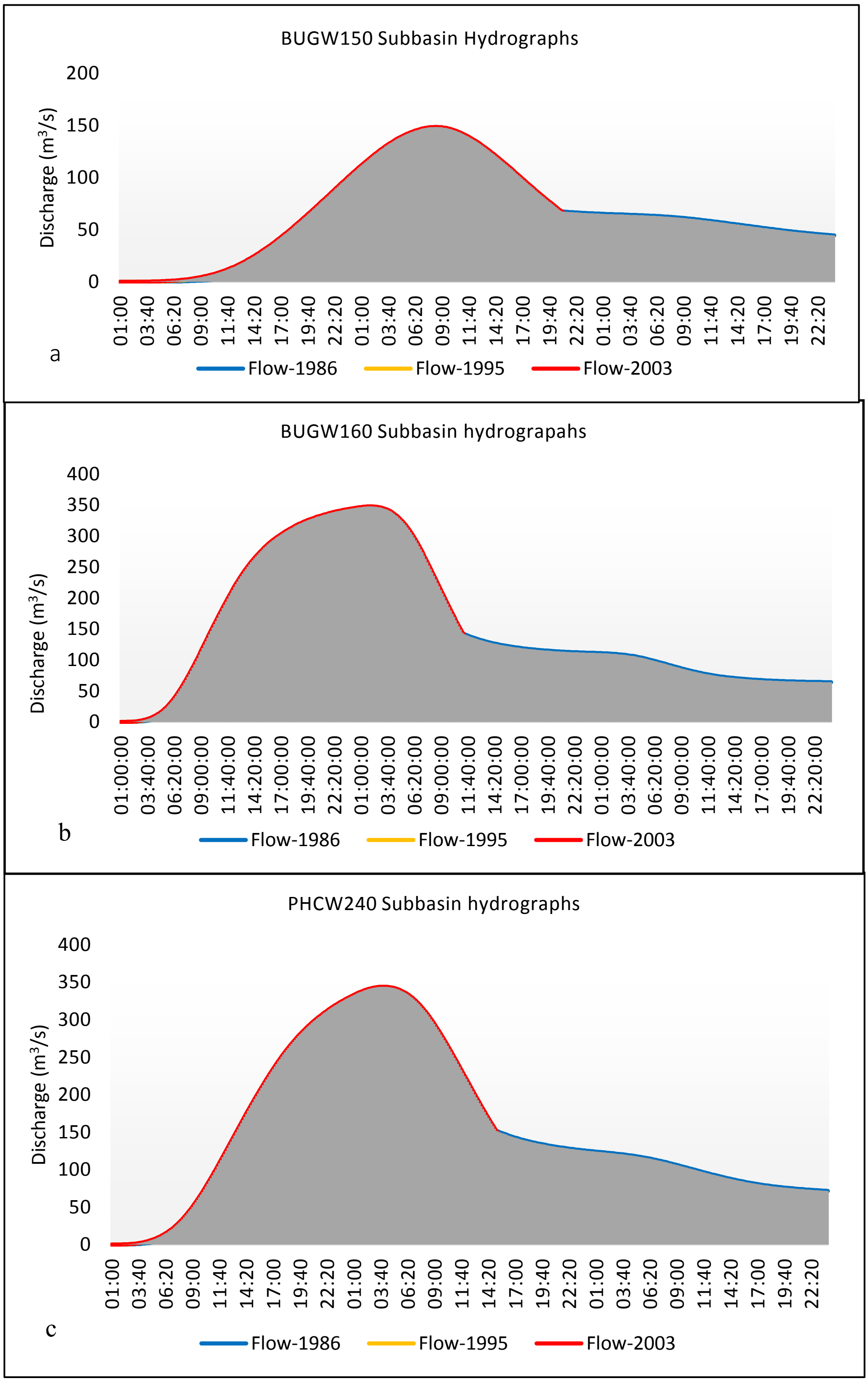

Figure 6.5 Subbasin hydrographs showing historic changes in peak discharge due to urbanisation. Figure 6.5 a, b and c represent hydrographs for subbasins BUG W150, BUGW160 and PHC 240.

The hydrographs in Figure 6.5 show the temporal dynamics in peak discharge in selected subbasins. All three hydrographs show the progressive rise in peak discharge, the highest peak flows were observed in the 2003 event. For example, peak flow in BUGW150 subbasin (Figure 5a) drastically increased by more than 100% from about 72 m^3/s in 1986 to 100 m^3/s in 1995, and to about 148.6 m^3/s in 2003. Similarly, in BUGW160, peak discharge surged from about 203 m^3/s in 1986, to about 254 m^3/s in 1995, to about 344 m^3/s in 2003, i.e. a 100% change.

In terms of spatial variation in peak flow, results under the 1986 column of Appendix 6.8 showed that peak flow values in downstream subbasins were not higher than those in upstream subbasins. Moreover, peak flow values increased in upstream subbasins as storm size and paved surface increased. For example, in the 1986, only AOW60 in the Andoni-Ogoni basin had a high Q_P; however, by 2003 other upstream sub basins also experienced high Q_P values. In summary, the result shows significant changes in the magnitude of runoff in the watershed, along with pronounced changes in runoff in many subbasins.

6.3.5 Historical Effects on Runoff due to changes in the urban area.

To analyse the historical effects of urban dominated changes on runoff, the study compared two historical urban scenarios, U_1 and U_2. For $U_{1,}$ 1986 land-use + 1986 storm data was used, while 2003 land-use +1986 storm data was used for U_2. In essence, urban land-use conditions were varied while storm size conditions were kept constant. In contrast to the above result, Table 6.7 shows that there was no significant change in annual maximum peak flow in the watershed due to urbanisation. Nevertheless, results show slight to considerable changes in peak discharge in the majority (33 out of 39) of local sub-basins (Appendix 6.9). Changes in Q_P by 2003 were significant in a number of subbasins including DEGW140, DEGW150, DEGW160, DEGW170, DEGW180, and DEGW190.

Table 6.7 Peak flow responses to two historical urban scenarios-U1 and U2. QP=subbasin peak discharge, %Δ= Percentage change from 1986. U1=1986 land-use + 1986 storm and U2=2003 land-use + 1986 storm. Peak flow results are based on data in Appendix 6.9.

Land-use scenarios	Input data	Rainfall Depth (mm)	Urban Area (km^2)	Percentage of watershed paved (%)	Peak Discharge-Qp (m^3/s)
U_1	1986 LU+1986 storm	104.3	135	7.5	206.8
U_2	2003 LU+1986 storm	104.3	550	12.9	206.7

6.3.6 Future Effects on Runoff due to changes in Storm and Urban area

Next, to analyse the potential effects of future urbanisation on peak flow, the future land-use digitised from the GPH Masterplan (UMP) was used directly as input to the validated HMS model. Another hypothetical urban scenario (UUMP) was generated based on the UMP (see subsection 4.7.2). In all, two future urban land-use scenarios (UMP and UUMP) and three potential storm scenarios (44yr, 57yr and 100yr) were used to examine the effects of increased storm and urban area. Appendix 6.1 presents the urban LULC raster map generated from the urban Masterplan layout. While Appendix 6.2 presents the raster map generated for the urban sprawl + urban Masterplan scenario. The UMP scenario was generated based on the assumption that the urban area would increase while all other land cover types would largely remain in the 2003 condition. Recall, UMP scenario was generated based on an assumption that urban area expanded when others remained almost the same, but in UUMP scenario, additional urban land represents urban sprawl areas was added upstream.

Based on the urban Masterplan, Table 6.8 shows that the future urban area is expected to rise rapidly by about 80%, from about 550 km^2 in 2003 to about 988 km^2 in 2060. This study projects that the percentage of impervious surface could increase from 12.9% in 2003 to 16.7% in 2060. In terms of the UUMP scenario, the result shows that the urban area is likely to increase in future to roughly 1239 km^2 with an increase in percentage of impervious surface to about 19% of the watershed. Meanwhile, the rainfall scenarios A2 (44yr), A1B (57yr) and 100yr are estimated to have storm depths of 183.7mm, 208.7mm and 290.1mm respectively.

Table 6.8 Peak flow response under different future urbanisation and rainfall conditions. Qp=annual maximum peak discharge, Δ%= Percentage change from 2003, Pre-urbanisation ratio = Qp of future scenario/Qp of 2003. Peak flow results are based on data in Appendix 6.10.

Scenarios	Rainfall Depth (mm)	Urban Area (km^2)	Percentage of impervious surface (%)	Peak discharge Qp (m^3/s)	% Δ (from 1986)	% Δ (from 2003)	Pre-urbanisation ratio (from 1986)	Pre-urbanisation ratio (from 2003)
1986	104.3	135	7.5	206.8				
2003	173.4	550	12.9	347.8	68.2		1.68	
2060-UMP (44yr)	183.7	988	16.7	369.4	78.6	6.22	1.79	1.06
2060-UMP(57yr)	208.7	988	16.7	418.8	102.5	20.42	2.03	1.20
2060-UMP (100yr)	290.1	988	16.7	583.5	182.2	67.78	2.82	1.68
2060-UUMP (44yr)	183.7	1239	19.0	369.4	78.6	6.22	1.79	1.06
2060-UUMP(57yr)	208.7	1239	19.0	418.7	102.5	20.42	2.02	1.20
2060-UUMP (100yr)	290.1	1239	19.0	583.3	182.1	67.78	2.82	1.68

Comparing changes in Qp due to 2003 and 2060 urban scenarios, the above result (Table 6.8) indicates that peak discharge is expected to rise significantly by 2060; however, the magnitude of change largely depend on the storm size. The greater the storm, the greater change in peak discharge. In other words, the magnitude of change largely depended on the size of the storm. The result for the UMP scenario (Table 6.8) indicated that the maximum peak discharge in the watershed is likely to rise by about 6%, 20% and 68% in the event of 44yr, 57yr and 100yr storm respectively.

6.3.7 Future Effects on Runoff due to changes in urban area.

Furthermore, analysis of changes based on future urban scenarios (UMP and UUMP) indicated that there is likely to be negligible or no increase in maximum annual peak flow due to the future expansion of the urban area (Figure 6.6). However, future urban expansion is expected to generate slight to considerable changes in some local sub basins (Appendix 6.10). More sub basins (9-12) are expected to experience pronounced changes in the event of the 44yr storm than in a 57yr storm event. Only one subbasin is expected to experience pronounced change in the case of a 100yr storm. Generally, future urban expansion is projected to have a negligible effect on annual maximum peak flow but is also likely to alter peak flow considerably in a number of subbasins. The magnitude of subbasins scale changes is mainly dependent on storm size. The greater the storm size, the smaller the effect of urbanisation.

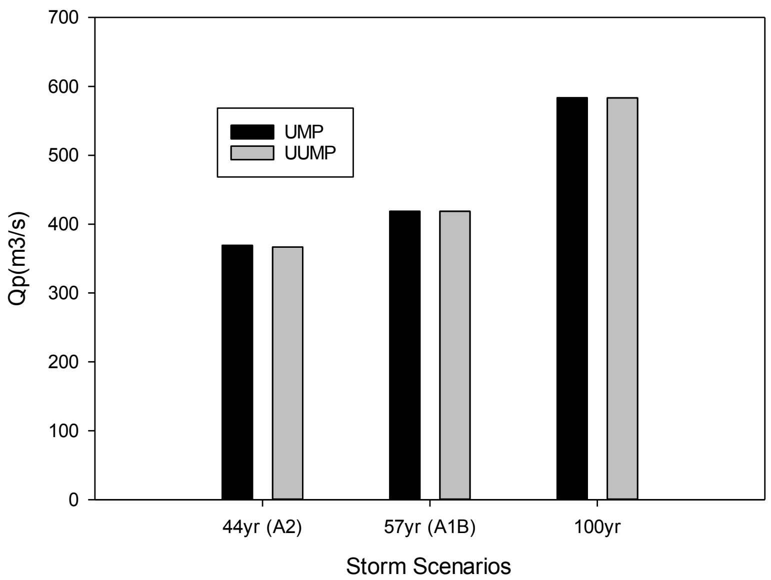

Figure 6.6 Bar chart showing changes in maximum annual peak flow as a result of future urbanisation under three storm scenarios.

6.3.8 Potential Effects of Afforestation on Runoff.

To examine the effects of afforestation on runoff in the GPH watershed, four future afforestation scenarios and three storm conditions used as input were compared (see subsection 4.7.2 in Chapter 4). The afforestation scenarios include the No forest (NF), urban Masterplan +urban sprawl (UUMP), low afforestation (LAF) and high afforestation scenarios (HAF), while the storm scenarios include 44yr, 57yr and 100yr storm.

Table 6.9 presents a matrix (result) of peak flow responses to afforestation and rainfall scenarios. Similarly, the result indicates that an increase in storm size is likely to have considerable to significant effect on annual maximum peak flow within the watershed irrespective of the amount of forest cover. For example, under the No-forest scenario, maximum peak is expected to change from about 367 m^3/s under A2 (44yr) scenario to about

419 m^3/s under A1B (57yr) condition, and finally to about 584 m^3/s under 100yr condition. That is, about 14% change in peak flow is expected between the 44yr and 57yr storm scenarios and roughly a 59% change expected between the 44yr and 100yr storm scenario. Moreover, a 39% change is expected between 57yr and 100yr storm conditions. Similar trends were alo observed under UUMP, LAF and HAF scenarios.

In contrast, the result also indicates that afforestation is likely to have no or a negligible effect on annual maximum peak flow in the watershed. In other words, there were no obvious changes in maximum peak flow due to the increase in forest cover (Table 6.9, Figure 6.7a). All future afforestation scenarios are projected to generate about the same magnitude of peak discharge. However, maximum Q_P under the No forest scenario is slightly higher than other storm scenarios. For example, under the 44yr scenario, peak discharge values were 367.3, 366.7, 366.7, 366.7m^3/s for NF, UUMP, LAF and HAF scenarios respectively, which means a 0.16% decrease in annual maximum flow between the No-forest and other scenarios. Hence, a similar trend was also observed when analysed under 57yr, 100yr storm scenarios. It also indicates that changes in peak flow depend more on storm size.

Table 6.9 Matrix of Peak flow responses under different Afforestation and Storm Scenarios

UMP means the urban Masterplan scenario. UUMP means an urban Masterplan + urban sprawl. NF means No forest. LAF means low afforestation and HAF means high afforestation. Results are based on data in Appendix 6.11.

	Afforestation scenario			
Storm scenario	NF	UUMP	LAF	HAF
44YR	367.3	366.7	366.7	366.7
57YR	419.4	418.7	418.7	418.7
100YR	584.1	583.3	583.3	583.3

Note all value are in m^3/s

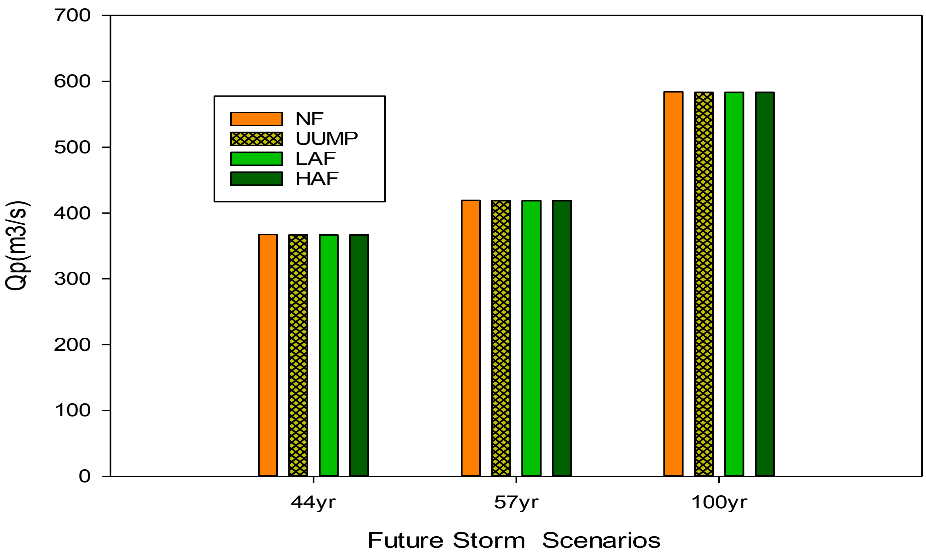

Figure 6.7a Bar chart showing effects of future afforestation scenarios on annual maximum peak flow or the watershed's response to afforestation of under three storm scenarios. UMP means the urban Masterplan scenario. UUMP means an urban Masterplan + urban sprawl. NF means No forest. LAF means low afforestation and HAF means high afforestation. Diagram shows that flow is not sensitive to afforestation.

Further analysis of potential effects of afforestation showed that increase in the area of forest cover is likely to produce different effects across all subbasins (Figure 6.7b). For example, Figure 6.7b displays afforestation effects under 44yr storm in selected subbasins. Qp in DEG W240 is projected to decrease from 225 m^3/s in an NF scenario to 212 m^3/s in a UUMP scenario, and up again to 225 m^3/s with more growth in forestland (i.e. LAF scenario), and finally down to 197 m^3/s with further growth in forest cover (in HAF scenario). Meanwhile, all forest scenarios are projected to generate about the same magnitude of peak discharge (170 m^3/s) in the PHC W220 subbasin. Forest cover is expected to cause a reduction in Qp in IMOW80 except for the HAF scenario. Generally, the effects of forest on subbasin runoff are very unpredictable.

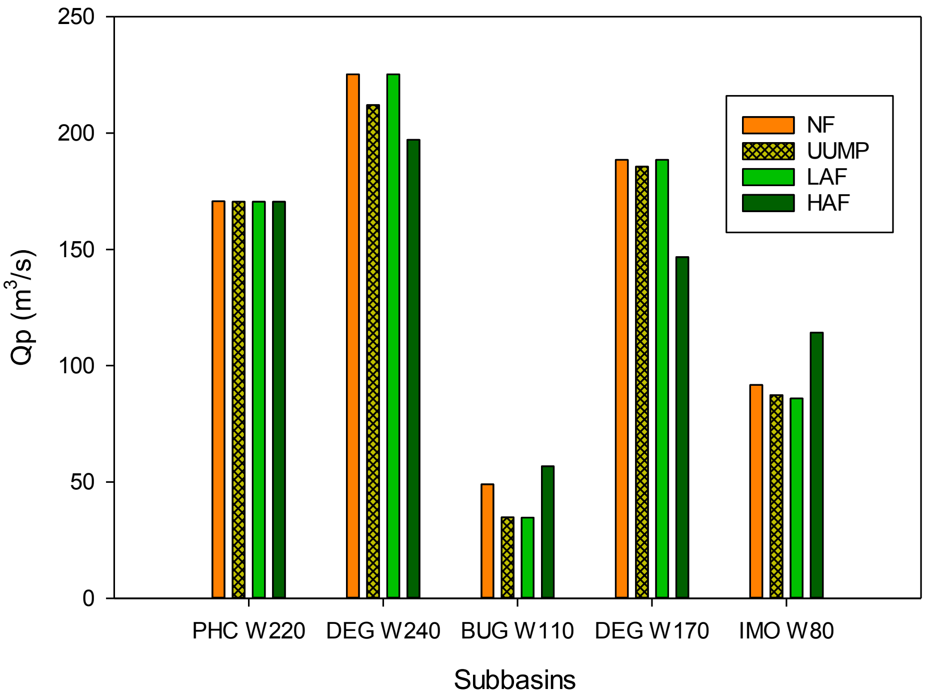

Figure 6.7b showing changes in Qp and the watershed's response to afforestation in selected subbasins under 44yr storm scenario. UUMP means an urban Masterplan + urban sprawl. NF means No forest. LAF means low afforestation and HAF means high afforestation. Diagram show the effects of afforestion varies for each subbasin.

6.3.9 Changes in Time of Peak.

To examine changes in the timing of peak flow for the entire watershed, the maximum and mean time of peak flow based on three historical scenarios T_{P1}, T_{P2} and T_U were compared (Table 6.10). T_{P1} and T_{P2} scenarios are the normal 1986 and 2003 land-use and storm conditions used as model input for analysing changes in T_P, whereas in T_{URB} scenario is a hypothetical scenario, in which a 2003 land-use and 1986 storm conditions were assumed and used as model input. T_{P1} and T_{P2} were compared to assess storm effects, whereas T_{P1} and T_{URB} were compared for urbanisation effect on timing. In this study, averaging of time of peak was done by summing the time of peak across all subbasins and dividing them by the number of subbasins. Maximum time of peak means the highest value of time of peak for each event (scenario).

Table 6.10 Statistics of Time of Peak. T_{P1} = 1986 land-use and storm conditions; T_{P2} = 2003 land-use + storm conditions; T_{URB}=2003 LU + 1986 storm.

Time of Peak Scenarios	Max Tp (Hrs)	Mean Tp (Hrs)	Std Dev
T_{P1}	58.5	35.8	11.0
T_{P2}	42.7	29.6	7.3
T_{URB}	57.7	35.0	10.1

Based on comparison of T_{P1} and T_{P2}, the result indicates that the quickest response time (42.67hrs) in the watershed occurred in 2003. In other words, time to peak was faster in 2003 than in 1986. Similarly, the table also shows that on average the time of peak was quicker in the 2003 event than the 1986 event. Analysis of variance showed a P-value of 0.026, which means the difference in the time of peak between the 1986 and 2003 events were statistically significant. In terms of the effect of urbanisation, the analysis of the TP_2 and T_{URB} scenarios showed that the time of peak was slightly quicker because of T_{URB} conditions. The average response time was also slightly higher due to T_{URB}. Analysis of variance showed P = 0.857, meaning there was no significant change in the time of peak because of urbanisation. This means that changes in runoff response time due to urbanisation are negligible.

6.3.10 Relative effects of Phase-1 Location alternative on Subbasin Hydrology

To compare the relative effects of the three hypothetical location alternative to Phase-1 project, spatial data for the Bori, current project and Omoku-Ogba alternative were prepared and used as inputs in the HEC-HMS. First, the Phase-1 project layout was mapped in ArcMap. The maps were then replicated and placed in the two other alternative locations. Ultimately, the analysis was performed for three different places situated in four basins. The Omoku alternative near Ogba is located north-west of the watershed in the Degema basin. The current project location in the middle lies between Port-Harcourt/Bonny and Buguma basins, whereas the Bori alternative is located south-east of the studied area and is situated in Andoni/Ogoni Basins (See Figure 6.8 for the position of the alternatives).

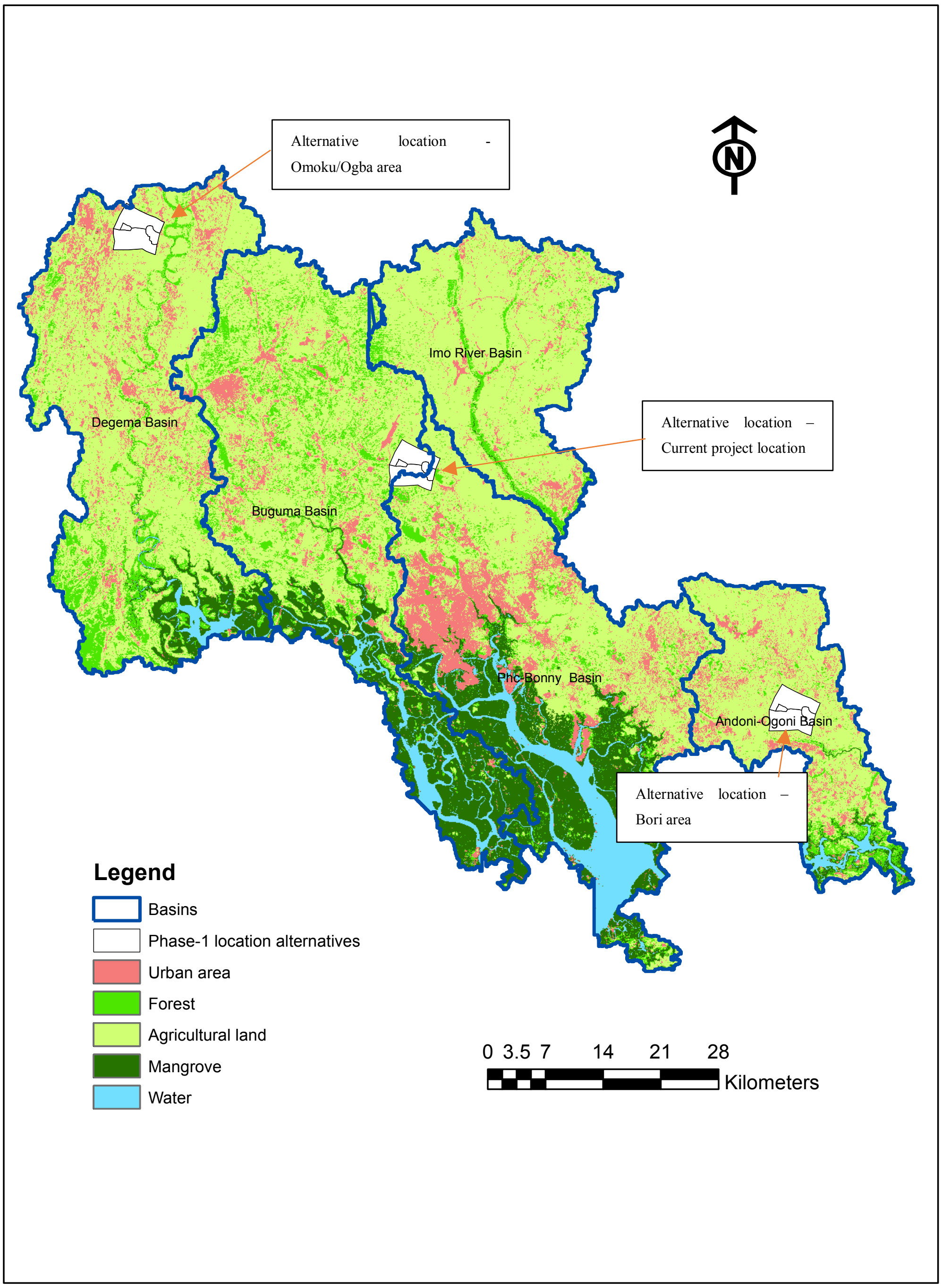

Figure 6.8 showing the three Phase-1 alternative locations analysed in this study. Base map is a classified LULC map for year 2003 obtained from the United States Geological Survey (USGS).

The result in Figure 6.9 demonstrates that Bori alternative generated the highest basin scale change in Q_P of about 9.3%, followed by the current project alternative, which caused a very slight change (of about 1.4%). The Omoku area alternative caused the least effect (a negligible change of about 0.7%). Based on the result, the effect of the current project alternative in the Port-Harcourt/Bonny Basin is negligible, but as stated above, Phase-1 development in the current project location had a higher effect on runoff than the Phase-1 development near Omoku area.

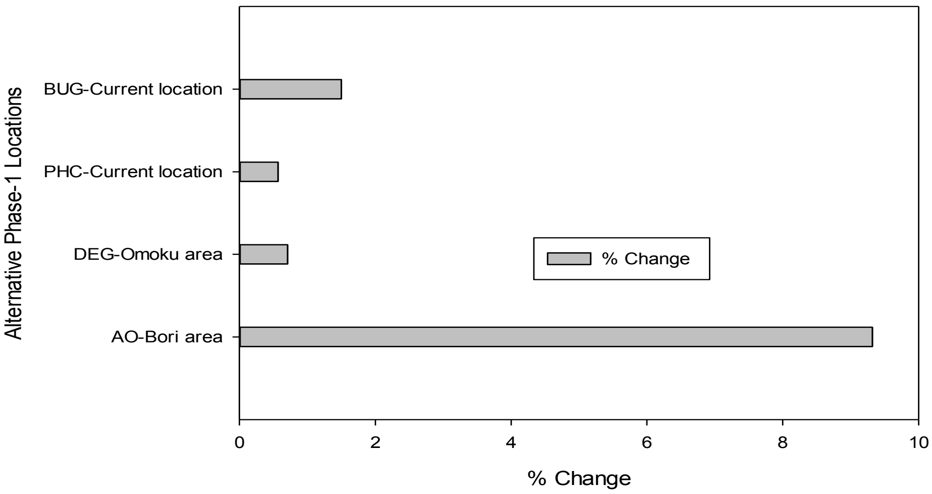

Figure 6.9 Basin peak flow response to GPH Phase-1 development in three alternative locations. It shows changes due to the Bori alternative location was considerably higher than changes in all other basins where the alternatives would have located. This plot is based on data in Appendix 6.12).

Figures 6.10 to 6.13 compare subbasin scale changes in Q_P due to project alternatives. Similarly, they demonstrate that the development in the Andoni / Ogoni Basin generated the most changes in Q_P, followed by the development in Buguma basin. Figure 6.11 shows that W50 and W40 will experience the most negative change (21 and 11%) due to the Bori alternative. The current location produced different effects in Buguma and Port-Harcourt/Bonny basins. About 9.0% and 5.0% change resulted in BUGW140 and PHCW210 subbasin respectively. Meanwhile, the least change was observed in DEGW140 due to the alternative development in the Omoku area. In general, Omoku alternative generated the least effect on runoff, followed by the current project location near the old city airport. The Bori alternative project location produced the worst effect on runoff in the basin and subbasin scale.

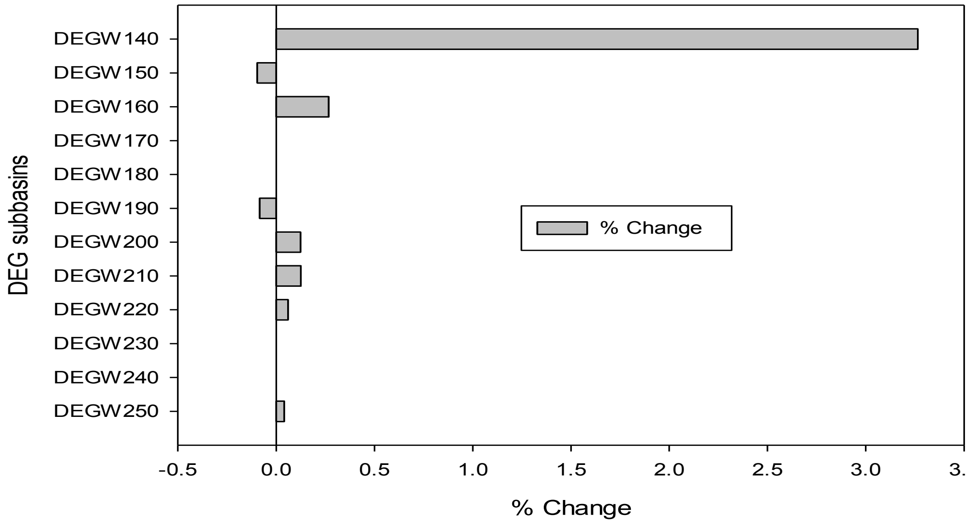

Figure 6.10 Subbasin peak flow response to Phase-1 alternative in Degema Basin. Changes in the right direction represent negative changes. It shows changes in DEG 140 is higher than changes in most subbasins in the Degema basin ((Plotted from Appendix 6.12).

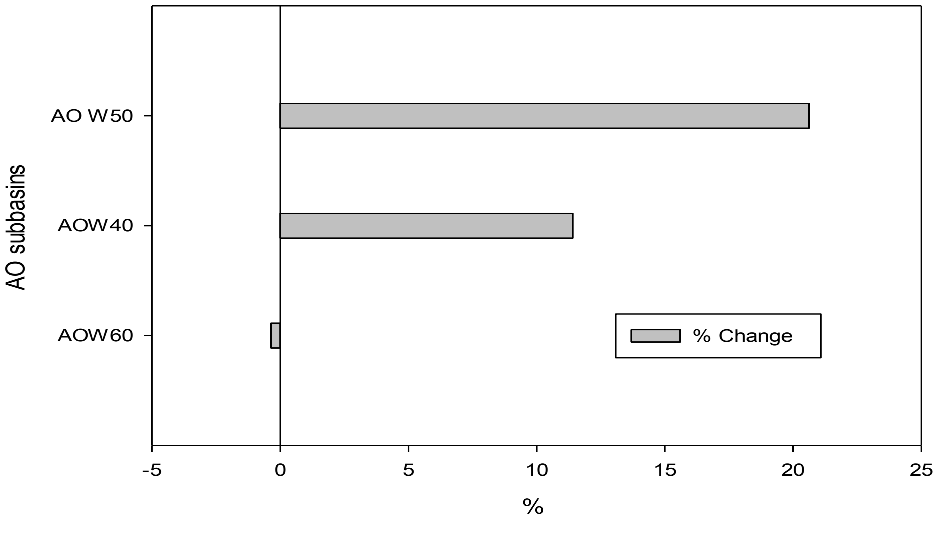

Figure 6.11 Subbasin peak flow response to Phase-1 alternative in Andoni-Ogoni Basin. Changes in the right direction represent negative changes. It shows changes in AO W50 and AO W40 are greater than changes in AO W60 subbasin ((Plotted from Appendix 6.12).

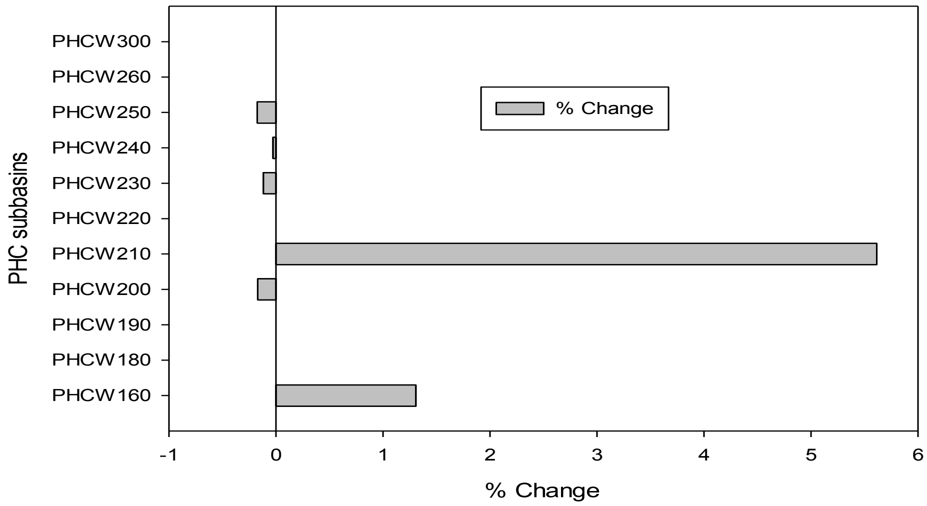

Figure 6.12 Subbasin peak flow response to Phase-1 alternative in Port-Harcourt/Bonny Basin. Changes in the right direction represent negative changes. That is changes in Q_P due to the Phase-1 development is greater than changes in Q_P due to the land-use condition in 2003 (Plotted from Appendix 6.12).

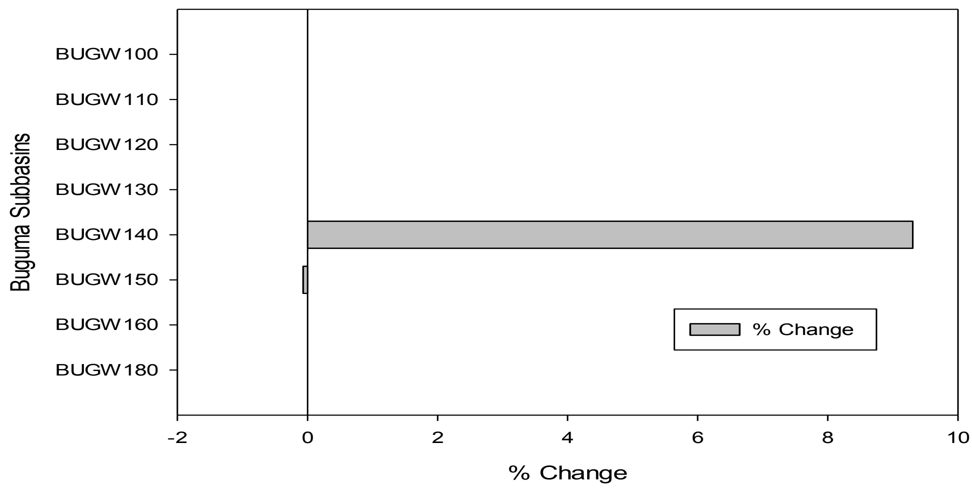

Figure 6.13 Subbasin peak flow response to Phase-1 alternative in Buguma Basin. Changes in the right direction represent negative changes. That is changes in Q_P due to the Phase-1 development is greater than changes in Q_P due to the land-use condition in 2003 (Plotted from Appendix 6.12)

6.4 DISCUSSION

Despite the lack of adequate data, the HEC-HMS model produced a reasonable performance when validated with observed data published in Okoro and Uzoukwu (2013). The results show how useful hydrologic model is for assessing hydrologic responses and predicting future outcomes for the watershed. Validated results were found to be within range when compared with related studies, e.g. Roy and Mistri (2013) and Knebl *et al.* (2005). Data scarcity remains a challenge in the study. Based on the model performance, this study supports prior studies such as Sorrell (2010); Roy and Mistri (2013), that alternative PUB approach that rely on physically based and conceptual models are suitable for producing reasonable estimates of changes in peak flow in ungauged watersheds.

6.4.1 Historical Effects on Runoff in the GPH watershed

Historically, this study found that annual maximum peak flow increased by approximately 35% in 1995 and by about 68% in 2003 from the 1986 base year. It is pertinent to point out that there some uncertainties in these results due to possible errors from the model itself, the quality of spatial and topographic input data used as stated in subsection 4.4.1. However, the results were deemed reliable after validation with independent data in published work, which showed a reasonable performance. Moreover, there were overestimation in some results and underestimation in others which would cancel themselves out and result the uncertainty having an insignificant effect on the result. The main point is that changes in extreme flow increased progressively and became significant by 2003. This finding is consistent with the view that the effect of rainfall on peak runoff strengthens as the percentage of impervious area increases (Lazaro, 1990). Although the rise in maximum peak flow corresponds to the increase in urban area, paved area and storm size (Table 6.3 and Figure 6.1), there were no obvious changes in annual maximum peak flow due to urban expansion alone (Table 6.8). Much of the changes can be attributed to increased rainfall. Hence, this study concludes that rainfall is the main driving force of change in maximum peak flow in the watershed, which is consistent with findings in other studies, e.g. Parker (2000); Singh *et al.* (2006).

Despite the dominant role of rainfall in the GPH watershed, it was found that urbanisation had a considerable impact on non-extreme peak flows in a number of local subbasins (Appendix 6.9). Affected subbasin includes, for example, BUGW100, DEGW250, and DEGW240, with the greatest effect in DEGW160. On a basin scale, the study also found that the effect of urban expansion was higher in Degema basin, which is not a much urbanised basin. In a nutshell, the effect of rainfall on annual maximum peak flow in the watershed was significant while the effect of urbanisation was substantial in local subbasins. Ultimately, this indicates that runoff was influenced by multiple factors such as land-use and changes in meteorological conditions.

Regarding the effect of urbanisation on runoff, the difference in percentage of change depends on scale considered. For example, findings of this study show the magnitude of change varies considerably from findings in a number of hydrologic studies when the entire catchment is considered. For example, for an experimental basin near Guelph in Ontario, Cook and Dickinson (1985) found a three-fold increase in maximum peak discharge due to urbanisation. Du *et al.* (2012) who assessed urbanisation effects for the Qinghai River Basin in China found a 3.5% increase in peak flow due to a 17% change in urban land between 1988 and 2009. Similarly, Kuprianov (1977) found a 10% increase in average discharge in an experimental study in Minsk, Belarus, whereas a four-fold and a twofold increase were found in the suburbs and the metropolitan areas in Moscow respectively. Lvovich and Chernishov (1977) also found a 50% increase in the Moscow River. Meanwhile, Gregory (1974) found a two to three-fold increase due to sub-urbanisation of the Exeter Catchment (Hollis, 1975). In contrast, this study concluded that there was no detectable change in maximum peak flow considering changes. However, there was slight to significant (1-76%) changes in the majority of subbasins (Appendix 6.9). This means the effect of urbanisation on runoff in this watershed depends on the scale considered. The impact of urbanisation in this study area is negligible when considered at the watershed scale, but ranges from small to significant at a sub-basin scale.

Findings in this study are also similar to findings in a handful of studies that found that urbanisation had no discernible effect on peak flows or floods. For example, Dudley *et al.* (2001) found that there was no significant change in peak flows despite a large increase (161%) in the paved surface in a catchment situated in southern Maine, USA. Similarly, a hydrologic simulation model was used by the USGS to simulate the annual peak discharge. The study found that both developed and undeveloped areas will experience about the same amount of flow peaks for a 2yr, 5yr, 10yr, 25yr, 50yr and 100yr recurrence intervals. Despite an increase from 3% to 37% impervious area, Wibben (1976) found no obvious change between flood frequency characteristics for rural and urbanised basins, which ranged from 4.1 to 165.8 km^2

in the area. Likewise, despite an increase in the impervious surface from 7.5 to 12.9% in this 4821km^2 watershed, there no obvious change in annual maximum peak flow due to increased urbanisation (Table 6.8). However, there was dramatic increase in a number of local subbasins as shown in Appendix 6.9.

Using Pre-urbanisation ratio.

In terms of the pre - urbanisation ratio, Leopold (1968) in his work concluded that increase in annual flood could rise between 1.5-6 times after urbanisation. For the GPH watershed, the results indicate that the historical increase was not more than 1.76. Although this result is within range, it suggests that the magnitude of change experienced in the entire GPH watershed is smaller than changes encountered in some basins is Leopold's study. One possible explanation for the difference may be due to the difference in size of catchment studied. It is widely held that changes in peak flow are more pronounced in smaller basins than large basins (Heggen *et al.*, 1996; Yair and Raz-Yassif, 2004). The GPH watershed spans about 4821 km^2, whereas basins analysed by (Leopold, 1968) were not more than about 2.6km^2. Similarly, Hollis (1975) concluded that low frequency floods (e.g. 100yr) might be doubled in size by the complete urbanisation of a catchment if that urbanisation leads to 30% paving of the basin. The model estimate in this study reveals that flow peak could triple in size after implementing the urban Masterplan (Table 6.8). However, further analysis reveals increased flow peak may not result from increased urbanisation.

In general, Q_P increased significantly by 2003 and is attributed to increased storm size. Urbanisation had no obvious effect on annual maximum peak flows, however, its effect on peak flow in a number of local subbasins was substantial. Based on the analysis, the most affected basin was the Degema basin.

6.4.2 Future effects of storm on runoff in the GPH watershed.

Regarding the future effects of storm on flooding, the model result revealed that the maximum peak flow significantly depend on storm size in the event of a 44yr or 57yr or 100yr storm (Table 6.8 and Figure 6.6). As expected, the result suggests that future annual maximum flow will be sensitive to increased storm. Compared to the 2003 base year, the analysis projects that IPCC's A2 (44yr) or 183.7mm and A1B (57yr) or 208.7mm storm scenarios are expected to generate a slight change to considerable changes (about 6% and 20%) in maximum peak discharge respectively, whereas the 100yr or 290.1mm storm scenario is expected to generate the most significant change in annaul maximum peak discharge. But when compared to the 1986 event, changes in all future scenarios were significant. Bear in mind that some assumptions were made when constructing the future land-use change scenarios and these could have implications on the result. In addition, possible errors from the land-use classification and digitisation, (see subsection 4.4.1) could have bearing on the result and generating additional uncertainties. Again, the projection of 100yr using a regression method could also increase uncertainties in the result; however, the important point to note is that changes in storm size cause considerable changes in maximum peak discharge.

Similar to historical events, it implies that the future annual maximum peak flow will increase if future storm increases. The phenomenon is supported in previous studies (Singh *et al.*, 2006). For example, Singh found that ±10% increase in rainfall resulted in ±3·5% increase in streamflow. In this study, about a 6%, 20% and 67% increase in rainfall is also likely to generate approximately 6%, 20% and 67% in maximum peak flow respectively. This clearly indicates that rainfall is the main driver of flooding in the watershed.

The A2 and A1B scenarios describe a heterogeneous future world with regional economic development and a future world with very rapid economic growth. Results in this study (Table 6.8) suggest that flood magnitude is expected to increase in the watershed, regardless of the scenario analysed. More so, rarer storms (such as 100yr) are likely to have a greater impact on flooding in the watershed. The worst floods often result from heavier, shorter, and extremely intense storms (Parker, 2000). Greater Port-Harcourt lies in the tropics where intense rainfall often occurs in the tropics (Parker, 2000; Eric Lambin *et al.*, 2003; George *et al.*, 2012; Halwatura and Najim, 2013). The difference between an A1B and the 2003 storm is 30mm. That means an increase in storm size of 30mm is likely to have considerable negative impact on floods in the studied watershed. For this reason, adequate measures should be put in place to mitigate the effects of moderate to low-frequency storms.

6.4.3 Potential effects of future urban land-use changes on runoff in the GPH watershed.

In terms of future urbanisation, the analysis revealed that obvious changes in future annual maximum peak flow are likely not to occur due to increase in urban extent (Table 6.8). Based on the land-use change analysis in Chapter 5, increased urbanisation of about 80% and 125% are projected due to the difference in urban extent in the UMP and UUMP scenarios respectively. Consequently, no discernible change in maximum peak flow is anticipated to occur in the watershed. At the same time, slight to considerable changes (of 0.5-17%) in peak flows are likely to occur in (about 12) local subbasins (Appendix 6.10). Therefore, the impact or effect of urbanisation depends on the scale considered. Urbanisation is likely to have little or no effect on future annual maximum peak flow at a watershed scale, on the other hand, urbanisation is projected to have considerable negative impact on peak flows in some subbasins. In this watershed, the effect of urbanisation is expected to decline as storm recurrence intervals increase. The AOW40, AOW50, BUGW100, IMOW70 IMOW80, IMOW100 subbasins are likely to experience considerable changes while BUGW130 is projected to experience the most change. In the BUG sub-basin, percentage change decreased from about 17% under 44yr storm to about 15% under the 57yr storm and down to about 11% change under the 100yr storm scenario. Again, keep in mind that there are additional uncertainties with the result due to the data quality and assumptions made during sparial data preparation and scenarios development. These could have affected results in this study; however, the results were deemed reliable after validation showed a reasonable performance. Moreover, some data sources are more uncertain than others are. There are uncertainties in this result but they are not multiplying, so they are not biased towards one direction.

Prior research has generated conflicting results in terms of the effects of urbanisation on runoff in other watersheds. For example, a number of studies have documented urban-induced changes in runoff (Hollis, 1979; McColl and Aggett, 2007; Chen *et al.*, 2009; Hejazi and Markus, 2009; Poelmans *et al.*, 2010; Ali *et al.*, 2011; Du *et al.*, 2012), In this studies, peak flow increase in varying degrees. Ali *et al.* (2011) found that future land-use as envisioned in the Masterplan is expected to raise the peak discharge to between 45.4 and 83.3% in the Lai Nullah Basin in Islamabad, Pakistan. The study strongly correlated increase in the magnitude of peak discharge to the expansion rate of the built-up area. In contrast, this study attributes changes in the magnitude of peak discharge in the watershed to rainfall. Similarly, Du *et al.* (2012) found that 11.8% and 14.0% expansion in built-up areas (based on 2002) potentially could raise the peak discharge by 1.6% by 2020 and 3.3% by 2050 levels in the Qinghai basin in China. The projected magnitude of change is relatively lower in the Qinghai Basin watershed than in GPH watershed. For the North-eastern US watershed, Brun and Band (2000) found that urbanisation would cause a significant increase in runoff at a threshold percent of impervious surface ranging from 20 to 25%. In the study, the watershed area is likely not to encounter a dramatic increase in peak runoff due to 19% impervious cover, but may produce a more dramatic effect in local subbasins.

The effects of urbanisation are rather complex in the GPH watershed. This model showed an interesting result. There was no increase in future annual maximum peak flow. Again, when considering storm-related effects, a significant (6 to 68%) increase in annual maximum peak flow is projected for the watershed; hence, this increase can be attributed more to changes in the storm magnitude for two reasons. First, both historical and future analyses showed that the watershed is more sensitive to rainfall than land use changes (Figure 6.6 and Table 6.8). Second, the historical and future analyses of the effects of urban change showed that urbanisation alone has little or no influence on the watershed's annual maximum peak flow values. Some key studies support this finding. Notably, Hollis (1977, 1979) in his work showed that changes occurred similar to findings in this study. The study showed that there was no difference in maximum monthly discharge in large floods ≥ 20yr. Likewise, Shuster *et al.* (2005) argued this behaviour can be explained by the theory that higher storms saturate catchments easily. Afterwards, the watershed surface tend to behave like impervious surfaces, such that further increase in urban cover no longer affects the peak flow (Parker, 2000; Du *et al.*, 2012). This behaviour may also be attributed to the reduction of storage capacity in suburban catchments.

Despite the minuscule effect on maximum peak flow on the watershed scale, the study argues that urbanisation is likely to have a considerable subbasin scale effect in some local areas. Possible explanations for increased peak flow in affected basins may include reduced infiltration capacity due to urbanisation; changes in dominant flow regime from saturation overflow to Hortonian overland flow in affected subbasins. Other co-factors may include subbasin morphometry; increased hydraulic efficiency, location and geometry of the impervious area. Regarding basin response, the finding that urbanisation effect declines with a higher return period in the GPH watershed is supported by key studies, e.g. Hollis (1975) Jones (2000a) and may also be influenced by the reduction in storage in suburban catchments. These findings demonstrate that the magnitude of change is different in this watershed and the effect depends on the scale considered. Future urbanisation as in the past, it is expected to affect time to peak and make a number of subbasins more prone to flash flooding.

6.4.4 Effects of Afforestation on Flooding.

Generally, the analysis in this study (Figure 6.7a) reveal that changes in forest cover are likely to produce little or no change in maximum peak flow. In other words, afforestation is likely to cause little or no decrease in maximum peak in the watershed. However, afforestation in projected to cause slight to considerable changes (-0.1% to -28%) in peak flow in about 19 out of 37 sub-basins. It is important to note that additional uncertainties could result due to assumptions made as well as possible errors from combination of data and from digitisation of future urban extent. However, the results were deemed reliable because the model estimates were reasonable during model validation. Forestation is often considered useful for flood mitigation (Brooks, 1985; Lane *et al.*, 2005; Buytaert *et al.*, 2007), this is due to forest effects on evaporation losses and the resultant reduction of peak discharge. Although, results of the effects of forest on flood in small catchments are conflicting in studies (Shuster *et al.*, 2005), they are relatively more straightforward than results of forest effect on flooding in large catchments. Earlier studies include the work of Hibbert (1967), and Bosch and Hewlett (1982) and more recently, Best *et al.* (2003) and Andréassian (2004). They agree that afforestation reduces annual discharge. Similarly, Scott and Lesch (1997), showed that afforestation in a small catchment caused a statistically significant decrease in streamflow.

In contrast, the effect on large catchments is relatively more unclear in studies, as no consensus has been reached so far. For instance, Wilk *et al.* (2001) in their work were unable to distinguish changes due to a reduction in vegetal cover; whereas, Bart and Hope (2010) concluded that the effects of deforestation on streamflow was more dependent on post-fire wetness conditions than deforestation. Meanwhile, Jones and Grant (1996) found that forest harvesting amplified peak discharge by as much as 50% in small basins and 100% in large basins over the past 50 years in the Western Cascades, Oregon.

On the contrary, in this study, it was found for the GPH watershed that increased vegetal cover is likely to cause a decrease peak flow in a number of the local basins. However, at the watershed scale, there is could be no significant decrease in maximum peak flows. In other words, there could likely not to be major changes in maximum peak flow due to increase in vegetal cover. However, there is likely to be a significant change in maximum peak flow due to increased storm. The latter is consistent with the work of Robinson and Newson (1986) who argued that changes in the magnitude of maximum flow peaks depend upon the rainfall profile. It was also found in this study that the effect of vegetal cover on peak flow declined with increased return period (Appendix 6.11). This means afforestation may not be an effective means of mitigating extreme flows in the watershed. However, afforestation could be used to mitigate frequent and small floods in a number of subbasins. The biggest changes were observed in three sub-basins (BUG110, BUG120, and BUG13). Hence, for effective flood risk management, it is important that hydrologists and planners understand the runoff dynamics of local subbasins.

6.4.5 Effects of developmental alternatives on subbasin hydrology.

Based on the model results (Figure 6.9-6.12), analysis of the relative effects of the three Phase-1 alternatives showed that the Omoku-Ogba location alternative generated the least change in peak flow (Figure 6.9). Changes due to the Omoku-Ogba, and current project location alternative was negligible. In contrast, the Bori location alternative generated the most change in peak flow even at the subbasin scale. Note that there are uncertainties with the results relating to alternatives due to possible errors from digitisation, data quality and the model error itself, these may have some effect on the result outcome but the result was considered reliable because the model validation was reasonable. Moreover, the uncertainties where not multiplying and so they were not biased in one direction. The result in Figure 6.9 mean that these developments in different locations (basins) with the same spatial extent had different effects on peak discharge in the studied watershed. The result of this study is consistent with Glasson’s view. Glasson *et al.* (2013) suggested that different location alternative are likely to generate different effects.

Moreover, studies suggest that the location or placement of impermeable surfaces (IS) within a basin of the watershed can have significant influence of watershed hydrology (Mejía and Moglen, 2009; Su *et al.*, 2014; Du *et al.*, 2015). Du *et al.* (2015) showed that an increase in the upstream IS amplified peak flow 14 times more than the same increase in downstream IS in the Longhua Basin, China. In contrast the location of the Phase-1 development did not have significant impact on peak flow in the basins (Appendix 6.16 and Figure 6.9). This is because change caused by the Bori alternative (located downstream) is 13 times higher than the change caused by the Ogba-Omoku alternative (located upstream). Hence, the magnitude of change may rather be influenced by the size of the basin since the effect of urbanisation is more pronounced in smaller basins. In this context, the Andoni-Ogoni basin (where Bori alternative is located) is the smallest basin.

It is also widely acknowledged that land-use changes affect the hydrology of catchments (Leopold, 1968; Hollis, 1975; Oleyiblo and Li, 2010). From a hydrologic standpoint, placing the development in the Omoku-Ogba area would have been the least disruptive. Hence, results from the hydrologic model could be useful for decision-making in land-use planning. It could also be useful for assessment and comparison, in choosing alternatives. According to DEAT (2004: 5), "location alternative are particularly relevant in a change of land use applications". Although factors such as proximity to the old city could be considered before selecting an alternative during land-use planning, in hydrology, alternatives with the least impact on peak flow are important (Leopold, 1968). From a hydrology point of view, it could be important for planners and developers to understand the dynamics in different subbasins. For example, the analysis (Figure 6.9) showed that the effect of urbanisation was greater in the Andoni-Ogoni Basin, where the Bori alternative is situated than in Buguma and Degema Basins, which is supported by the theory that the effect of urbanisation is more pronounced in smaller basins than larger ones. It is pertinent to note that the analysis and assumptions made for the alternatives used in this study are only used for academic purposes, as decisions for the Phase-1 project have already been made. The analysis in this study was used to demonstrate the importance of hydrologic models for aiding land-use and EIA decision making and the implications of location alternative in hydrology as well as the importance of development location in hydrology. The findings in this study also showed that the greatest changes in peak discharge were observed in subbasins where developments were placed. (See Figure 6.8). For example, Figure 6.11 reveal that AOW40 and AOW50 experienced the most changes in the Andoni-Ogoni basin.

6.4.6 The Importance and Implications of changes in impervious cover and peak flow for the GPH watershed.

Increasing impervious cover from about 7.5 % to 14% in 2003 and about 17% in 2060 estimated in this study could exert multiple pressures and have severe implications for local subbasins. Importantly, the increase in the impervious cover may alter dominant flow regimes in the local subbasins as noted in (Shuster *et al.*, 2005). Vegetated humid regions are often more dominated by saturated overland flow runoff process (Heggen *et al.*, 1996; Jones, 2000b; Reddy, 2005). However, the predicted increase in impervious cover could cause a shift from the saturated overland flow process and partial subsurface flow processes to nearly all surface runoff in heavily urbanised subbasins. This could lead to relatively higher peak flows, shorter lag times, and ultimately result in severe and frequent flooding.

Next, increased imperviousness in subbasins could equally affect the watershed's aquatic ecosystem (Shuster *et al.*, 2005) and stream habitat quality (Tong and Chen, 2002; Brilly *et al.*, 2006). Again, impervious cover in the studied area is likely to rise from about 7.5% in 1986 to about 17% in 2060. Schueler (1994) found that aquatic ecosystems could be 'stressed' if the impervious cover is at 1–10%, 'impacted' at 11–25% impervious cover; and 'degraded' at 26 – 100 percent. This means aquatic ecosystems in the studied watershed could have been stressed since 1986 or may be impacted. It could also be severely impacted in future due to the GPH development. Regarding impairment of quality, Ruby (nd) reported that impervious cover at 10-25% causes 'major impact and is characterised by a reduction in habitat quality. Hence, impervious cover greater ≥ 25% may result in 'degraded stream' characterised by decreased water quality, loss of habitat, floodplain connectivity, and bank stability. This suggests in future; stream habitat quality could be severely impacted.

Increased peak flow due to urbanisation, a phenomenon observed in a number of subbasins in this watershed could have severe implications in the studied area (Oleyiblo and Li, 2010; George *et al.*, 2012; Verbeiren *et al.*, 2013). Changes in peak flow indicate variations in the magnitude and frequency of flooding (Brooks *et al.*, 1991; Du *et al.*, 2012; Halwatura and Najim, 2013). Based on the findings in this study, severe and frequent flooding are some of the main concerns likely to worsen in the local sub-basins. In particular, the indication that urbanisation is expected to have adverse effects on subbasin peak flow suggest more people may become vulnerable to frequent flooding. This study recommends that planning and watershed management should be carried out on a subbasin-by-subbasin basis. Therefore areas projected to suffer increased peak flow should be a priority for flood risk management.

Floods occur due to extreme flows (Yevjevich, 1992). Likewise, the indication that increase in rainfall could have a significant effect on maximum peak flow suggests that many more people are likely to be exposed to frequent and severe flooding in the watershed at large. Historical results indicate that increased peak flows in a number of subbasins were accompanied by shorter lag times due to urbanisation. It implies that those subbasins are likely to become more prone to flash flooding. Apart from the frequency and severity of flooding, other environmental issues associated with increased runoff may be the increased impact on surface water quality (Álvarez-Cabria *et al.*, 2016), ecology (Fabricius, 2005), groundwater (Harbor, 1994) and soil. Urban runoff remains an important source of nonpoint pollution (Heggen *et al.*, 1996). Frequent overland flows may pick up potential pollutants, including sediments, nutrients (e.g. from fertilizers), bacteria (e.g. from animal and human waste), metals (e.g. roads and rooftops), pesticides (e.g. from lawn and garden chemicals), petroleum by-products (e.g. from leaking automobiles). These may present difficulty in developing procedures to minimise impacts.

Increased runoff and frequent flooding due to urbanisation may accelerate soil erosion by dislodging and transporting soil particles, especially in areas with sparse vegetation (Biddoccu *et al.*, 2016). This process may affect light reduction due to increased turbidity. Soil erosion may eventually lead to reduction of productivity in upland areas and increased sedimentation in downstream areas (Fabricius, 2005). Increased runoff can also affect the recharging of water tables with a corresponding decline in base flows, which has implications for the ecology of streams (Simmons and Reynolds, 1982). Lastly, the increased exposure to sediment load, pollutants and nutrients discharged from the upland area may affect downstream ecosystems. Hence, improved understanding of the runoff dynamics in local subbasins is critical for planning and flood risk management.

6.4.7 Applicability of Research

Findings from this study suggest that urbanisation could have little or no effect on annual maximum peak flow watershed at watershed scale. At this same time, it indicates there is a potential for increase in peak flow in a number of subbasins due to the effect of urbanisation. Although this study was conducted for the Greater Portharcourt watershed, the results could also be generalised to other watersheds and subbasins within the Niger Delta region that have similar climatic and physiographic setting. In other words, urbanisation may have little or no significant effect on annual maximum peak flow in large watersheds around coastal cities such as Warri (west of the delta) as well as Uyo, and Calabar (east of the delta). However, a number of subbasins in these areas could suffer significant increase in flooding.

Beyond the Niger Delta, the phenomenon observed the study area could also be applicable to other watersheds and cities in tropical deltas. For example, tropical watersheds in the Dagupan region in the Philippines, Lieu Province in Southern Vietnam, Cao Phraya Delta in Thailand, the Mekong Delta in Vietnam and Mahanadi Delta in India. Tropical deltas contain some of the most important urban and industrialised developments in the world and as such present several challenges given the diverse character and location of land-water interface (Chu, 2010). Like Greater Portharcourt areas, large populated centres such as Dhaka in Bangladesh, Bangkok in Thailand and Hanoi in Vietnam are important for industrial development (Chu, 2010). Characteristically, the climate of these regions is tropical and ever wet. Mean temperature of the coldest month is greater than 18C, with duration of wet season over 4.5months. Usually, the intensity of rainfall in these areas is usually high (Bonell *et al.*, 2005). Like the GPH area, it means rainfall would be most likely be the main driving force of flooding at watershed scale due to large storm size. Due to the wetness of the area, the antecedent moisture content of their watersheds are likely to be high. In these areas, urbanisation could also have similar effect on flooding at subbasin scale like in the GPH watershed, given the similarities in their climatic and physiographic characteristics.

Moreover, the approach used in this study could also be beneficial for poorly or ungauged watersheds in other developing countries. Flood risk management and planning require good estimates of streamflow and peak discharge at different points within a watershed. Observed streamflow data are important for calibrating and validating models in order to understand hydrologic changes in watersheds. The International Association of Hydrological Sciences (IAHS) recognised this as a challenging problem and declared the previous decade (2003–2012) the “decade of the ungauged basin”. To overcome this problem, some alternative schemes known as the prediction in ungagged basin (PUB) was adopted. One way of achieving PUB in this study was by routing the channel streamflow using a physically based Muskingum-Cunge method in which model parameters are derived from physical catchment attributes. In situations where flow data are available, the simple Muskingum routing method has often been used to rout channels based on storage-discharge relationship (Chow et al., 1988). It is used to model the volume of flooding in channels using a combination of wedge and prism storage. The key parameters in Muskingum routing are K (travel time) and X (weighting coefficient). These parameters are best derived from stream flow measurements. However, the Muskingum-cunge method used in this study has the advantage over other routing methods and the simple Muskingum method in that its coefficients are physically based and are derived from catchment characteristics. Moreover, the method produce consistent results (Brunner and Gorbrecht, 1991). Therefore, the method can be applied in many data sparse regions such as sub-Saharan Africa and Asia as well as other ungauged watersheds.

6.5 CONCLUSION.

The objectives of this chapter are threefold. To assess the historical and future effects of rainfall and urbanisation on runoff. To assess the extent to which afforestation could minimise flooding in the future and to assess the effects of Phase-1 location alternative on runoff. The results of this research indicate that the annual maximum peak flow increased progressively in the past and became significant (68%) in 2003. Depending on storm size, annual maximum peak flow could increase significantly in future by up to 68% compared to 2003 baseline. This significant historical change coincide with the increased rate of urbanisation, but further analysis reveals that the increased rate of urbanisation had little or no effect on annual maximum peak flow at watershed scale. Therefore, it is argued that the significant changes in annual maximum peak flow within the historical period is attributed to increased storm size than urbanisation in the studied watershed. That is, urbanisation did not have significant effect on maximum annual peak flow in the watershed. Nevertheless, further findings suggest the effect of urbanisation on runoff was considerable in a number of subbasin. This is due to the slight to significant changes in peak flows in majority of the subbasins. Based on these findings, it was concluded that the effect of urbanisation on floods in this watershed depends on the scale considered. There was little or no effect on flood at the watershed scale, in contrast the impact of urbanisation on flow at the subbasin scale was substantial. The trend of change in the studied area is similar to findings in other areas, however, the magnitude of change in this area vary. On a watershed scale, Hollis (1975) similarly found there was no obvious change in maximum peak flow. Hence, this study concludes that the effects of urbanisation in the area are more pronounced in smaller subbasins, which is supported by these studies. Moreover, this study also found that the increased magnitude of subbasin peak flow were accompanied by a decreased time of peak.

Similarly, in the future, this study finds that changes in peak flow are projected to be significant (approximately 68%) by 2060, which vary from projected changes in other studies, however the magnitude largely depends on storm size. This study also concludes that the effect of urbanisation is likely to be substantial in a number of subbasins, however the impact is likely to diminish with greater storm size. This study also find that the effects of urbanisation are greater when evaluated on a subbasin scale. In a nutshell, the effect is negligible relative to the effect of storm size. Similarly, this study concludes that afforestation is likely to have negligible or no effect on extreme flows. Unlike urbanisation, afforestation presents a mixed picture in terms of progressive change in peak flow. For afforestation, different subbasins are likely to experience different effects under different afforestation scenarios irrespective of the percentage of forest cover. Lastly, analysis of the effects of three alternatives showed that the Bori location alternative situated in the smallest basin could have been the most disruptive in terms of changes in peak flow, which buttresses the point that urbanisation has greater effects in smaller basins. The study also finds that the placement of development within the basins did not significantly influence changes in peak flow. Therefore, planning should be carried out on a subbasin-by-subbasin basis to effectively reduce the risk of flooding. Lastly, greater attention should be paid to smaller subbasins such as AWO 50 and AWO 40. It is important to remember that there are some uncertainties with the model results due to possible errors from the model, digitisation, and land use classification as well as possible errors incurred due to the assumptions made, however, the results are deemed reliable because the model showed good performance during model validation. Again, the results are consistent with some published work.

Chapter 7. Effects of Urbanisation and Climate Change on the Flood Hazard in Greater Port-Harcourt Watershed.

7.1 INTRODUCTION.

This chapter presents the analysis and discussion of the impact of climate change and urbanisation on flood depth, extent and velocity in the study area. The chapter further present maps of flood zones to identify priority areas. It also presents damage potential map used for identifying potential areas and infrastructure at risk by means on their exposure to flood hazard. Climate change and urbanisation affect not just the hydrology of catchments as indicated in the previous chapter; It also affects channel hydraulic condition (Martens, 1968; Cook and Merwade, 2009; Azad Hossain, 2013). Several studies utilised advanced 1D, 2D, 3D hydraulic models and GIS software for predicting the potential effects on river flooding (Horritt and Bates, 2002; Van, 2010). Such information is vital for identifying priority and high-risk areas (Tate and Maidment, 1999; Horritt and Bates, 2002; Tingsanchali and Karim, 2005; Mohammadi *et al.*, 2014). It is also necessary for flood control planning, flood zoning, pre and post flood disaster planning as well as spatial planning (Yang *et al.*, 2006; Kourgialas and Karatzas, 2011; Tripathi *et al.*, 2014). In this study, flood zones were delineated to suggest appropriate flood mitigation measures for the area. Flood hazard assessment/ danger mapping was carried out to identify the priority areas and infrastructure at risk to flooding based on their exposure to high flood hazards

The primary objective of this chapter is to understand the historical and future impact of urbanisation and rainfall on flooding in GPH. A secondary objective of this chapter is to identify priority areas and infrastructure at risk to flooding based on their exposure to flood hazard. The three key parameters used include flood depth extent and velocity. Section 7.2 briefly summarises the methodology. Section 7.3 presents an analysis of hydraulic model results while section 7.4 present results from flood maps. Section 7.5 present discussion of this chapter and conclusion presented in section 7.5.

7.2 SUMMARY OF THE METHODOLOGY.

The detailed methodology used in the hydraulic modelling is presented in Chapter 4. This section provides only a summary. This study used a 1-D hydraulic model for predicting changes in flood depth, extent and velocity. Model data were further used to delineate flood zones and rate flood hazards for the GPH watershed. The hazard rating provides an assessment of the direct risk to life based on water depth, velocity of flow and debris factor, Based on prior experiments, the assessment recognises that debris-filled flowing water increases the danger to people (Van Alphen *et al.*, 2007; Moel *et al.*, 2009). Three important modelling procedures were the pre-processing, model run and post processing. HEC-GeoRAS, an ArcMap extension was used to carry out pre-processing. It involved the creation, digitisation and exporting of several RAS data including stream centreline, bank line, cross-sectional cutlines, flow path centreline, land use area, and connections in GIS format (Brunner, 2010). A total of 29 river reaches were delineated. Due to the very high drainage density of the area, major rivers that fall within the study area were digitised. SRTM DEM was used to create TIN. These geometric and elevation data were then exported into HEC-RAS model. Imported data in the RAS model were then corrected.

Afterwards, the steady-state flow data consisting of peak discharge, flow regime and boundary conditions were then entered. All historical and future urban flow data were then used as inputs to allow for comparison. In total, four historical scenarios (I986 or U1, 1995, 2003 and U2) were analysed. Likewise, six future scenarios (UMP44yr, UMP57yr, UMP100yr, UUMP44yr, UUMP57yr and UUMP100yr) scenarios were compared. U_1 and U_2 were the historical urbanisation scenarios compared in this study, while UMP and UUMP were the future urbanisation scenarios compared in this study.. Due to the nature of flow in the area, the mixed flow regime was selected for modelling these rivers. After the model run, the water surface profiles, and flood velocity data were obtained. HEC-RAS results were then exported back into in ArcMap for post-processing.

Finally, flood extent and flood depth maps were generated in ArcMap and used for mapping flood zones and damage potential. Three flood zones (low, medium and high probability) zones were delineated based on the 2.5yr (1986), 38yr (2003) and 100yr flood extents (See Appendix 7.5). The flood danger-map show hazard rating associated with 100yr storm flood. As earlier stated, it provides an assessment of the direct risk to life mainly arising from flood depth, and velocity and debris factor (Wallingford, 2005; Van Alphen *et al.*, 2007). The calculation of flood hazard rating was performed in ArcMap environment and is based upon a mathematical formula: HR = d x (v + 0.5) + DF developed by Middlesex University Flood Hazard Research Centre. Note debris factor of 0.5 was used in this study. This formula can be viewed in the

“Flood Risks to People – Phase II” report (HR Wallingford, 2005) and have been used in important studies such as Van Alphen *et al.* (2007). Due to data constraints in the study area, it a reliable method that uses fewer physical indicators to provide a damage potential value used for assessing the direct risk to life. Debris factor was integrated based on the assumption that debris-filled flowing water increases the danger to people, see Van Alphen *et al.* (2007). Note in this study, the assessment of direct risk to life was applied to road and rail users and not just floodplain dwellers.

7.3 HYDRAULIC MODEL RESULTS.

7.3.1 Model Validation.

Figure 7.1 shows the validation map and is based on a visual comparison of satellite river extent and model flood extent. Hence, the map showed a reasonable match between satellite and model river extent. As no model is perfect, there were slight overestimations and underestimations in some parts of the main channel, but in general, the HEC-RAS flood extent closely matches with the TM satellite map flood extent. Based on this validation, HEC-RAS was used for predicting impacts based on different urbanisation and climate change scenarios

Figure 7.1 showing model validation by comparing the modelled flood width and Landsat TM observed flood width for January 8, 2003. Overestimations can be seen at the bottom left corner of the map. Underestimations can also been seen at the top of the map.

developed in the study. Not all model data related to flood depth, flood extent and flood velocity can be found in Appendix 7.2, 7.3 and 7.4 respectively.

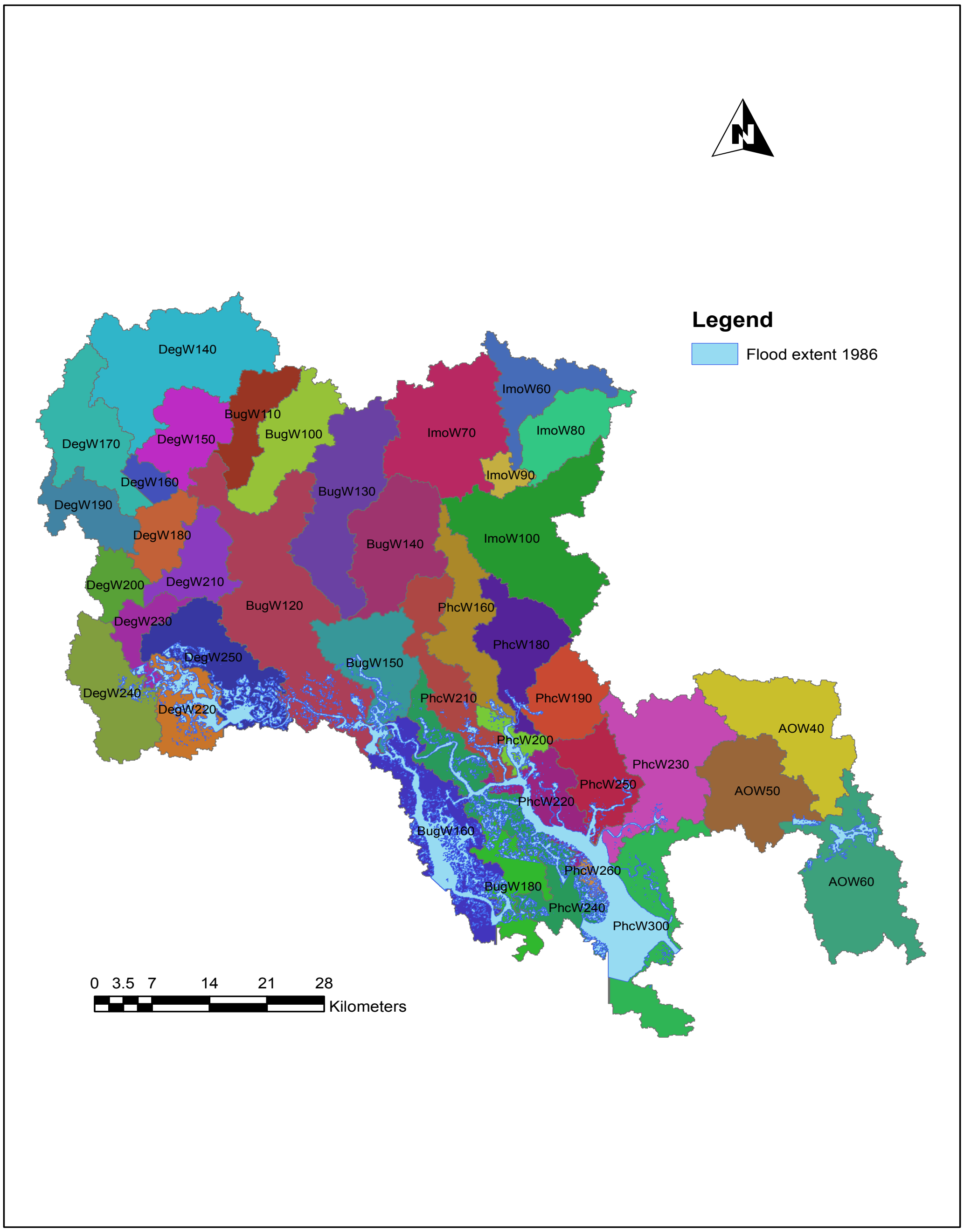

Figure 7.2 A 1:600,000 map showing the location of modelled major rivers within the extent of the studied watershed.

7.3.2 Impact on Flood Depth due to Increased Storm size and Urbanisation.

Figure 7.2 shows the input data extent and location of all modelled rivers within the watershed. Table 7.1 present comparison of the difference in flood computed for all scenarios. Based on the comparison of result outputs, Table 7.1 indicates that significant changes is flood depth occurred in the past and is projected to occur in future. Again like maximum peak discharge analysed in Chapter 6, little or no change is anticipated to occur due to increased urbanisation based on the analysis in Table 7.1. For instance, the multiple comparisons of changes in flood depth (Table 7.1) shows all changes in historical events were statistically significant (i.e. all P-values are less than 0.05). All future (storm dominated) changes are likely to be significant when compared to 2003 condition. Likewise, all future (storm dominated) changes in flood depth are likely to be significant when compared with changes due to storms of lower return period. In contrast, P-values is greater than 0.05 for all urbanisation dominated changes. That means, the impact of urbanisation on the flood depth was not significant in the past and likely not to be significant in future. In a nutshell, the impact on flood depth was significant historically and is expected to increase in the future. However, the projected significant change will largely be due to increased storm and not urbanisation.

Table 7.1 Multiple comparison of changes in flood depth computed for all historical and future scenarios for the entire modelled area. The table shows significant changes in historical and future flood depth. Rows shaded yellow rows indicate urbanisation based comparisons.

	Comparison	q	P	P<0.050
Historical	WSE 2003 vs WSE 1986 (U1)	9.935	<0.001	Yes
	WSE 2003 vs WSE Elev1995	9.936	<0.001	Yes
	WSE Elev1995 vs WSE 1986 (U1)	4.962	<0.001	Yes
	WSE U1 vs WSE U2		(P = 0.308)	No
Historical vs Future	WSE UMP100yr vs WSE 2003	13.464	<0.001	Yes
	WSE UUMP100yr vs WSE 2003	15.551	<0.001	Yes
	WSE UUMP 57yr vs WSE 2003	7.191	<0.001	Yes
	WSE UMP57yr vs WSE 2003	8.798	<0.001	Yes
	UMP44yr vs WSE 2003	3.954	0.014	Yes
Future	WSE UMP100yr vs UMP44y	12.213	<0.001	Yes
	WSE UMP100yr vs WSE UMP57yr	13.124	<0.001	Yes
	WSE UMP57yr vs UMP44y	5.19	<0.001	Yes
	WSE UMP44yr vs UUMPP44yr		(P = 0.904)	No
	WSE UMP 100yr vs UUMP 100yr		(P = 0.910)	No

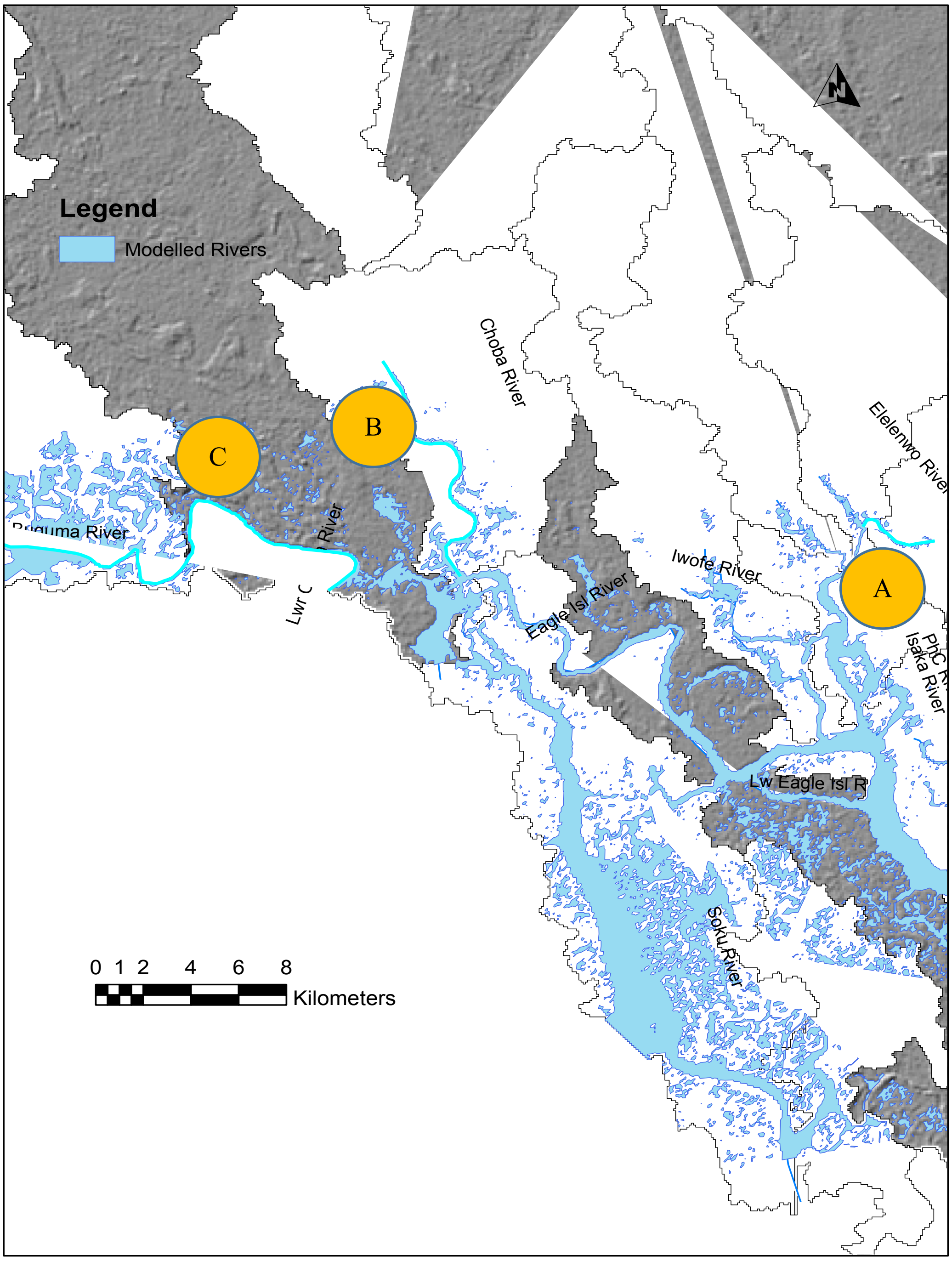

Figure 7.3 Map showing upstream reach locations for which changes in flood depths were analysed below. Location A shows the North Eleme reach, Location B shows the Choba River Reach and Location C shows the Buguma River Reach.

Figure 7.4 to 7.7 are examples of longitudinal reach profiles showing changes in water surface elevations due to increased storm and urbanisation. Three reaches were selected for analysis including the North Eleme, Choba and Buguma reach at Location A, B and C respectively (Figure 7.3). As shown in Figure 7.4 (graphs A, B and C), all three upstream reaches experienced incremental changes in flood depth in the historical events. For instance, between 1986, 1995 and 2003, flood depth increased substantially by approximately 1metre from about 3.8, 3.9 to about 4.6 m downstream of the North Eleme reach profile. In contrast, Figure 7.5B showed no changes in flood depth due to increased urbanisation between U1 and U2 historical scenarios. It is pertinent to note that there are uncertainties with the results relating to changes in flood depth due to possible errors from input data and the model error itself, these may have some bearing on the result outcome but the result was considered reliable because the hydrologic model validation showed good performance.

On the other hand, Figure 7.6 compares historical and future changes. As expected, incremental changes in flood depth were observed between 2003 and all future (UMP) scenarios. All three reaches at location A, B and C show incremental changes in flood depth due to increased storm. For instance, flood depth downstream of the North Eleme reach (A) is predicted to increase by about 1.5m. That is, from about 4.5m in 2003 to about 5.0m for the 44yr storm, about 5.2m for the 57yr storm and finally to about 6.0m for the 100yr storm scenarios. In contrast, Figure 7.7 demonstrates that little or no change is predicted to occur due to future urbanisation analysed in this study. In summary, analysis of changes in longitudinal profiles show that the degree of change in flood depth will vary from reach to reach. It also shows that a significant increase in flood depth is expected in the future. However, the major impact expected is largely as a result of increased storm and not urbanisation. Again as stated in the previous paragraph, the input data and digitisation may have generated additional uncertainties, but the results are considered reliable because of the performance of the model validation.

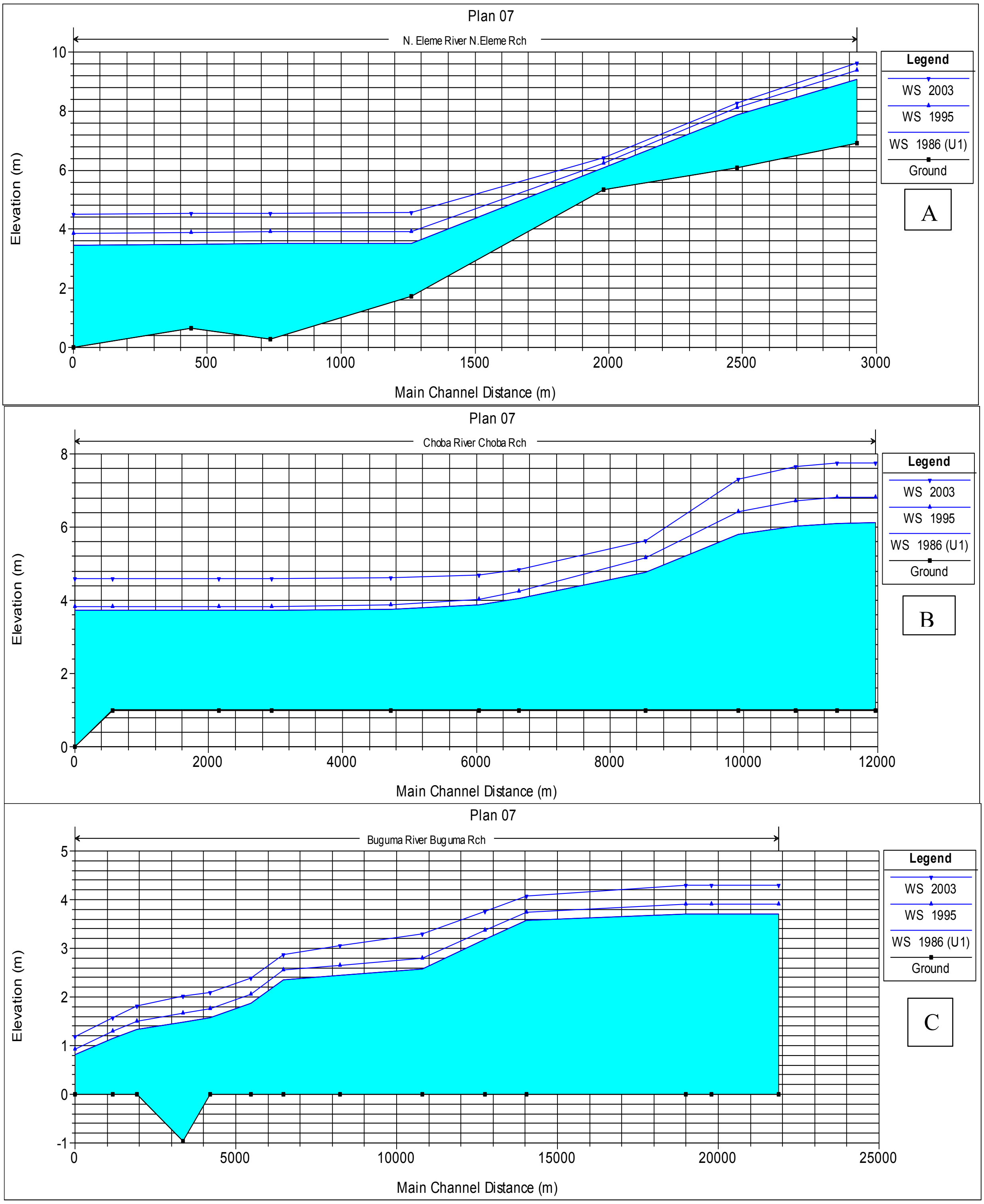

Figure 7.4 Longitudinal reach profiles showing progressive changes in flood depth due to 1986, 1995 and 2003 historical urban scenarios. North Eleme Reach is situated at location (A), Choba River at location (B) and Buguma at location (C) in Figure 7.3 map.

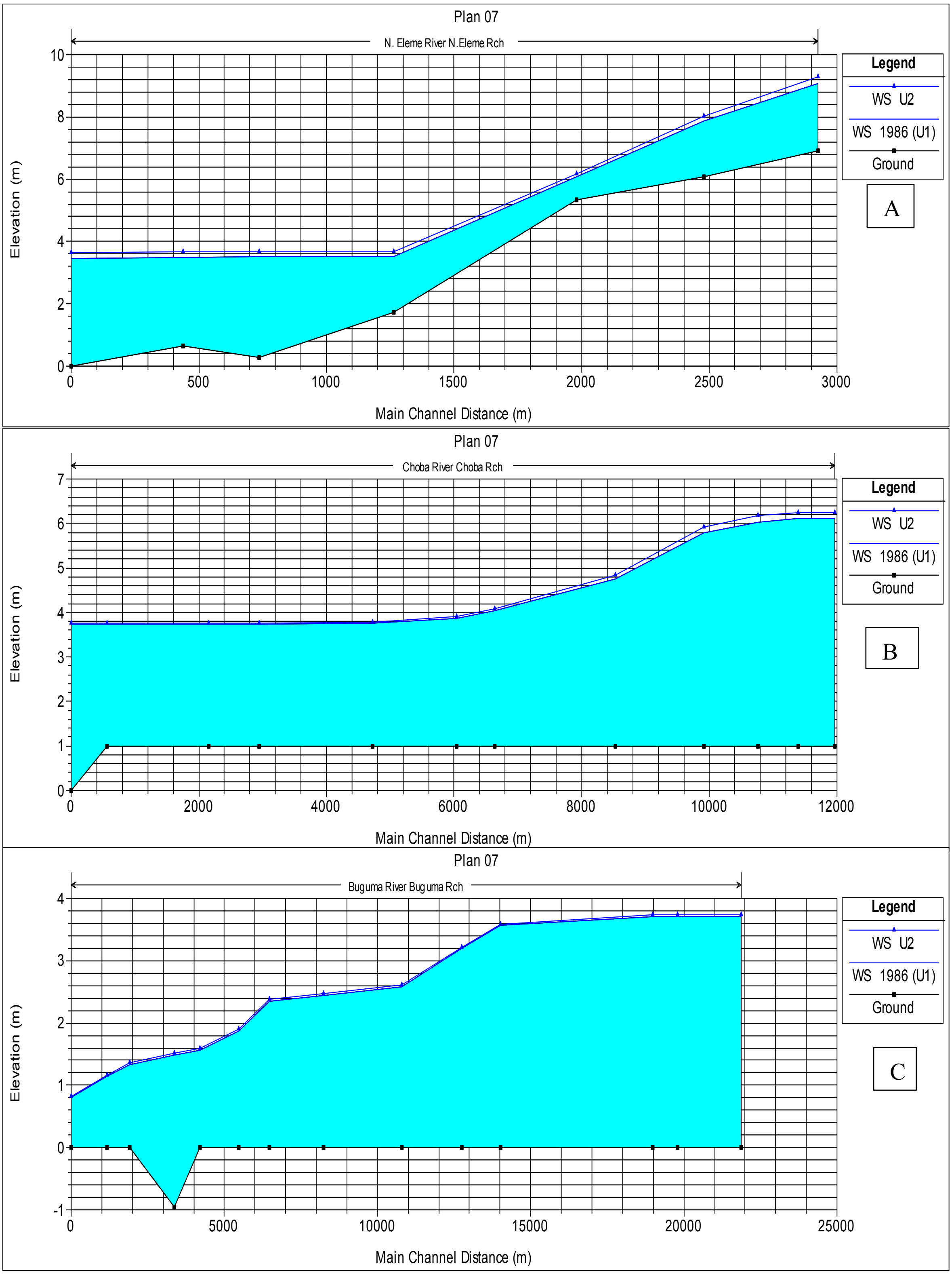

Figure 7.5 Longitudinal reach profiles showing small changes in flood depth due to changes in U1 and U2 historical urban conditions. U1 represents 1986 land-use + 1986 storm, while U2 represents 2003 land-use + 1986 storm. North Eleme Reach is situated at location (A), Choba Reach at location (B) and Buguma Reach at location (C) in Figure 7.3 map.

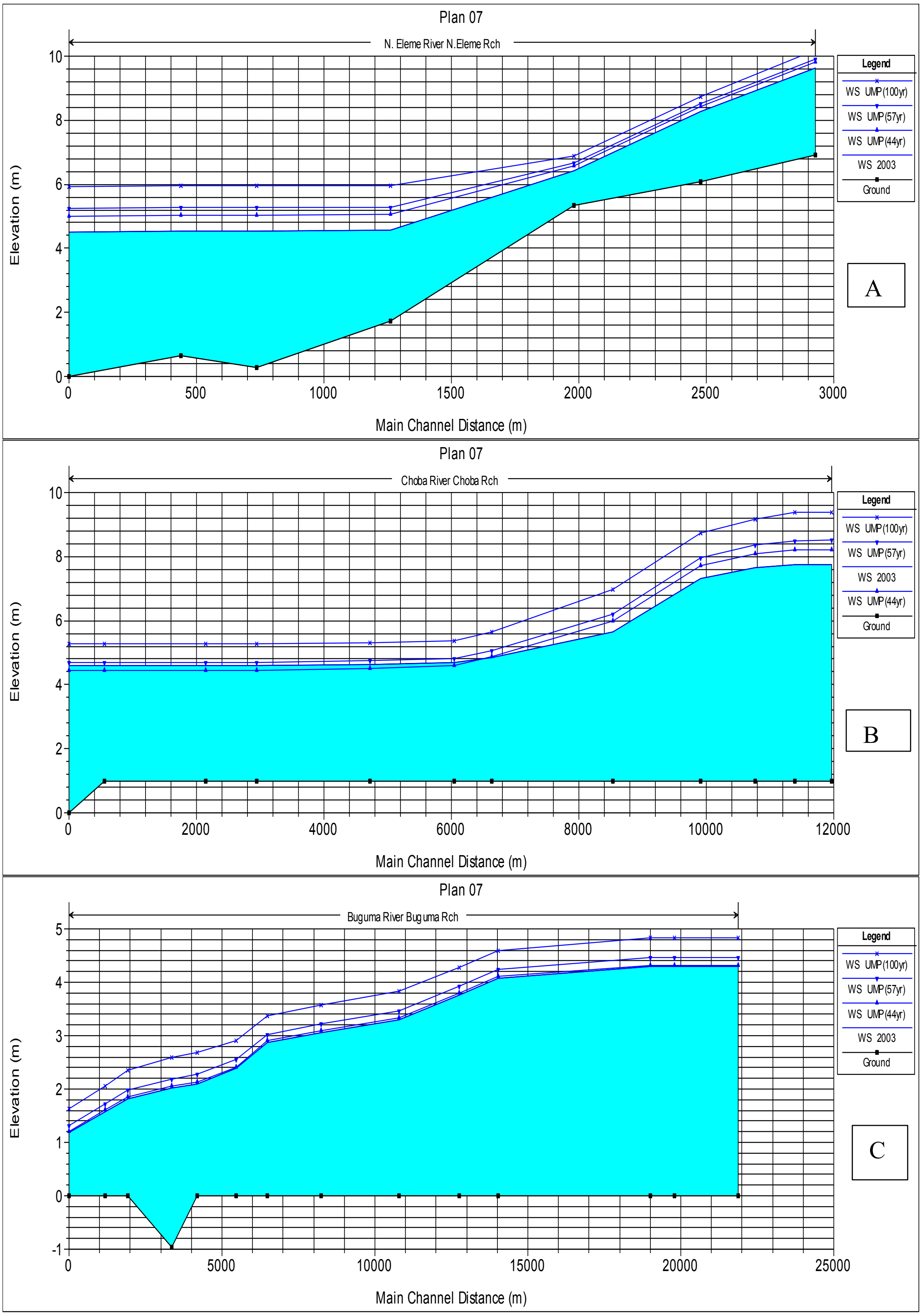

Figure 7.6 Longitudinal reach profiles showing significant changes in flood depth due to changes in historical (2003) and future storms (44yr, 57yr and 100yr). 44yr and 57y storms are based on the SRES A2 and A1B emission scenarios respectively, while 100yr is a hypothetical scenario. North Eleme Reach is situated at location (A), Choba River at location (B) and Buguma at location (C) in Figure 7.3 map.

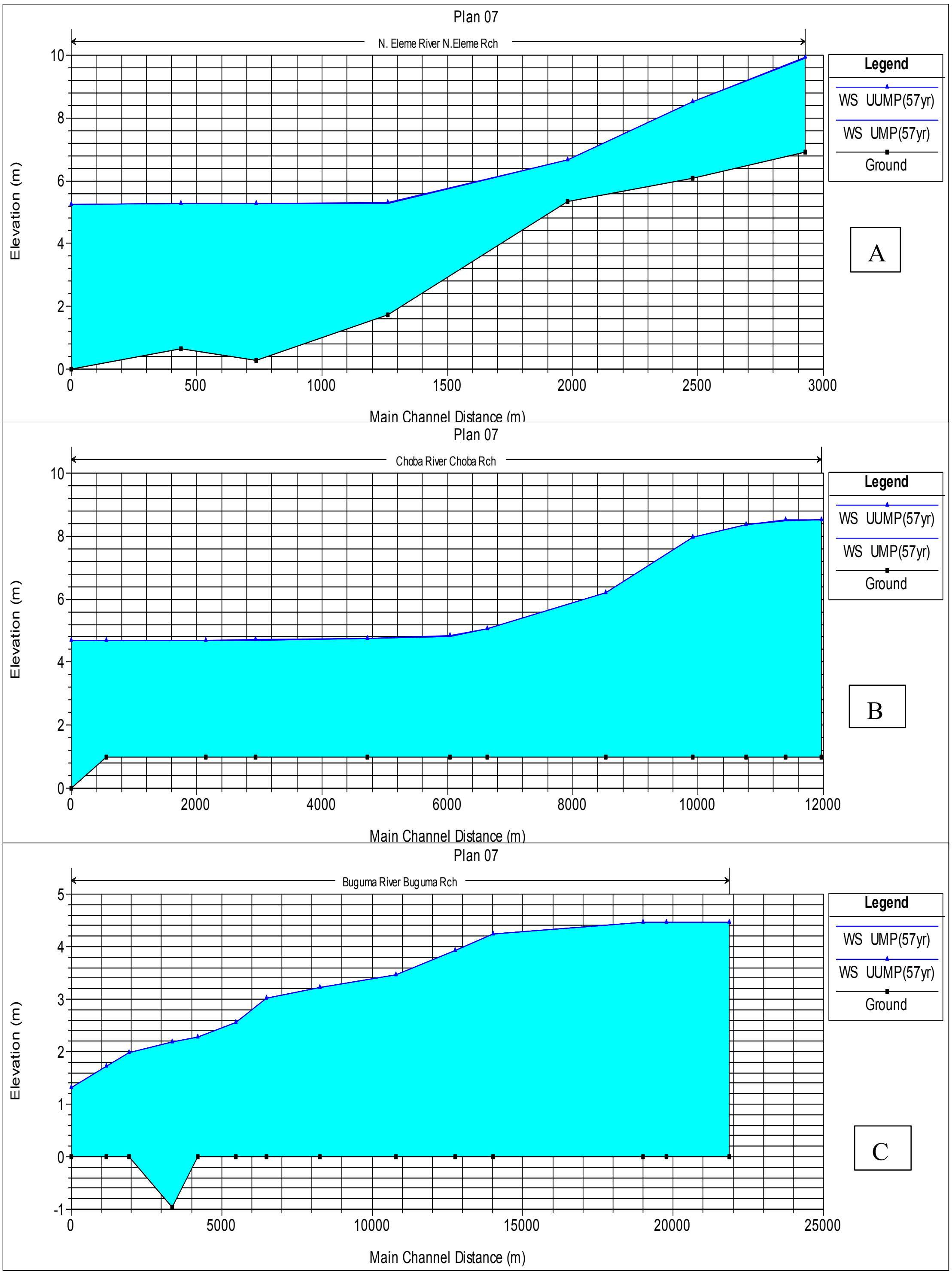

Figure 7.7 Longitudinal reach profiles showing no changes in flood depth due to changes in future urban conditions UMP 57yr and UUM57yr. UMP is based on the urban Masterplan, while UUMP is based on Urban sprawl + urban Masterplan. North Eleme Reach is situated at location (A), Choba Reach at location (B) and Buguma Reach at location (C) in Figure 7.3 map.

7.3.3 The effects of urbanisation and increased storm on Flood Inundation Extent.

The impact on flood inundation extent was analysed by estimating the total and percentage change. The historical flood extents were estimates for 1986 (U1), 1995, 2003and U2 scenarios, whereas future flood extents were estimated for UMP44yr, UMP57yr, UMP100yr as well as UUMP44yr, UUMP57yr, UUMP100yr scenarios. The results of total and percentage area change are summarised in Table 7.2 while Figures 7.8 to 7.11 presents overview maps of modelled flood extents.

Table 7.2 Statistics of land-use and climate change impacts on flood extent. Inundation extent historically increased by 15% between the 1986 and 2003 events. In future it is expected to increase considerable by about 20% in the event of a 100yr storm flood. There was apparently no historical and future changes in inundation extent due to urbanisation (in the yellow coloured rows). Note: negative values shown was acceptable in this study as the values were considered to lie in the margin of error.

Scenarios	Total Area Changes (km^2)	Δ from 1986 (%)	Δ from 2003 (%)	Δ U1- U2 (%)	%Δ UMP57 Yr- UUMP57yr
1986 (U1)	292.7				
1995	301.6	3.0			
2003	337.1	15.1			
U2	291.9			-0.3	
UMP44yr	338.4	15.6	0.4		
UMP57yr	359.4	22.8	6.6		
UMP100yr	402.7	37.6	19.5		
UUMP57yr	358.1				-0.4

Based on the results presented in Table 7.2, results from the HEC-RAS model indicates that considerable changes occurred in the past and considerable changes are expected in future however, the magnitude of change largely depend on the meteorological conditions and not urbanisation. From the above Table, the total inundation extent historically increased by about 15% between the 1986 and 2003 events. However, when compared to year 2003 condition in future, flood extent is predicted to expand slightly by about 0.4 and 7% in UMP 44yr and UMP57yr conditions. However, it is expected to increase considerably by about 20% due to UMP100yr conditions. However, when compared to 1986 scenario changes are predicted to be substantial in future. Comparatively, further analysis showed urbanisation had little or no impact on the extent of flooding in the past, and is likely to have little or no impact on flood extent in the future.

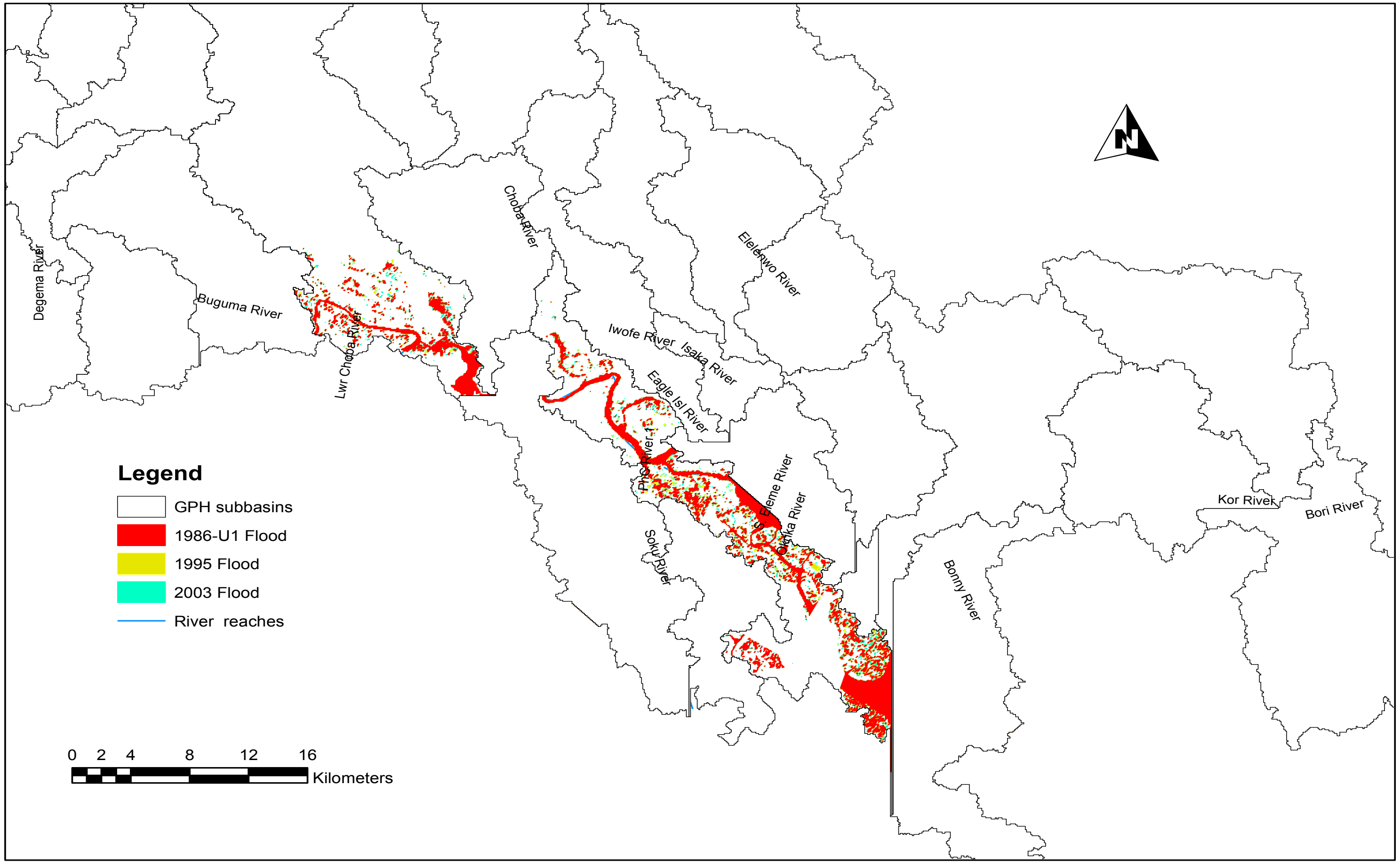

Figure 7.8 Overview map of modelled flood extent for the 1986, 1995 and 2003 events (Scale: 1:300,000).

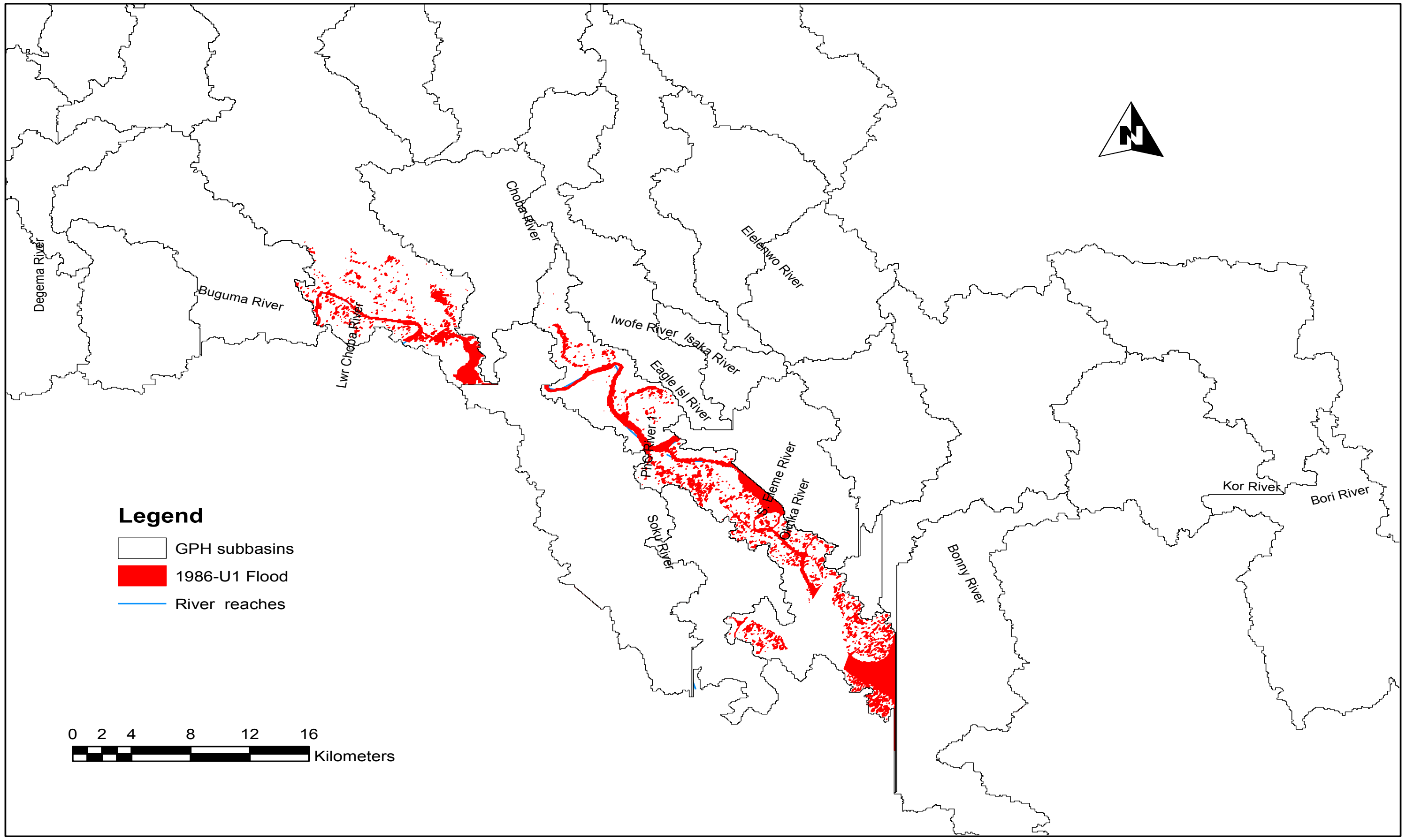

Figure 7.9 Overview map of modelled flood extent for the 1986 event (Scale: 1:300,000).

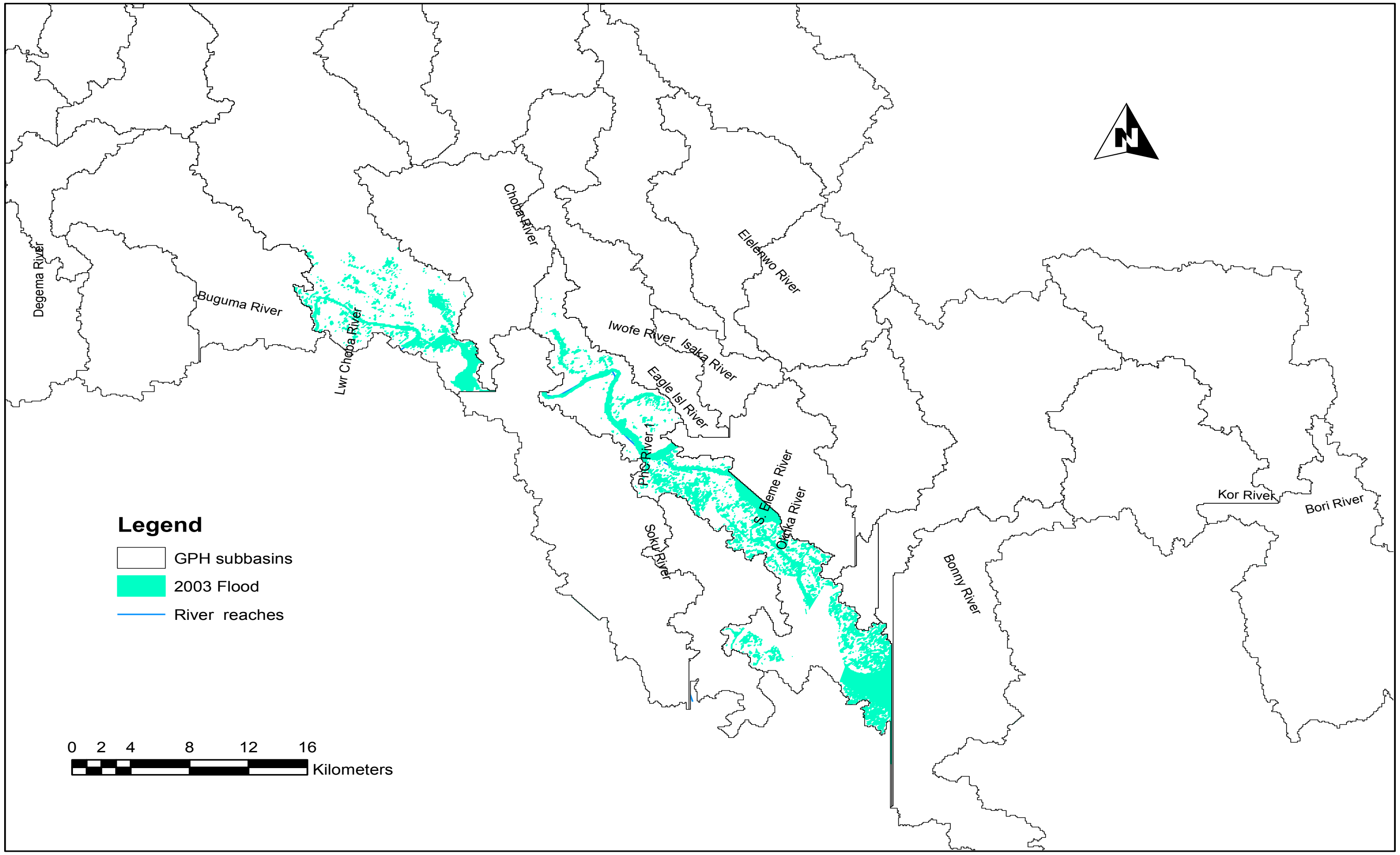

Figure 7.10 Overview map of modelled flood extent for the 2003 event (Scale: 1:300,000).

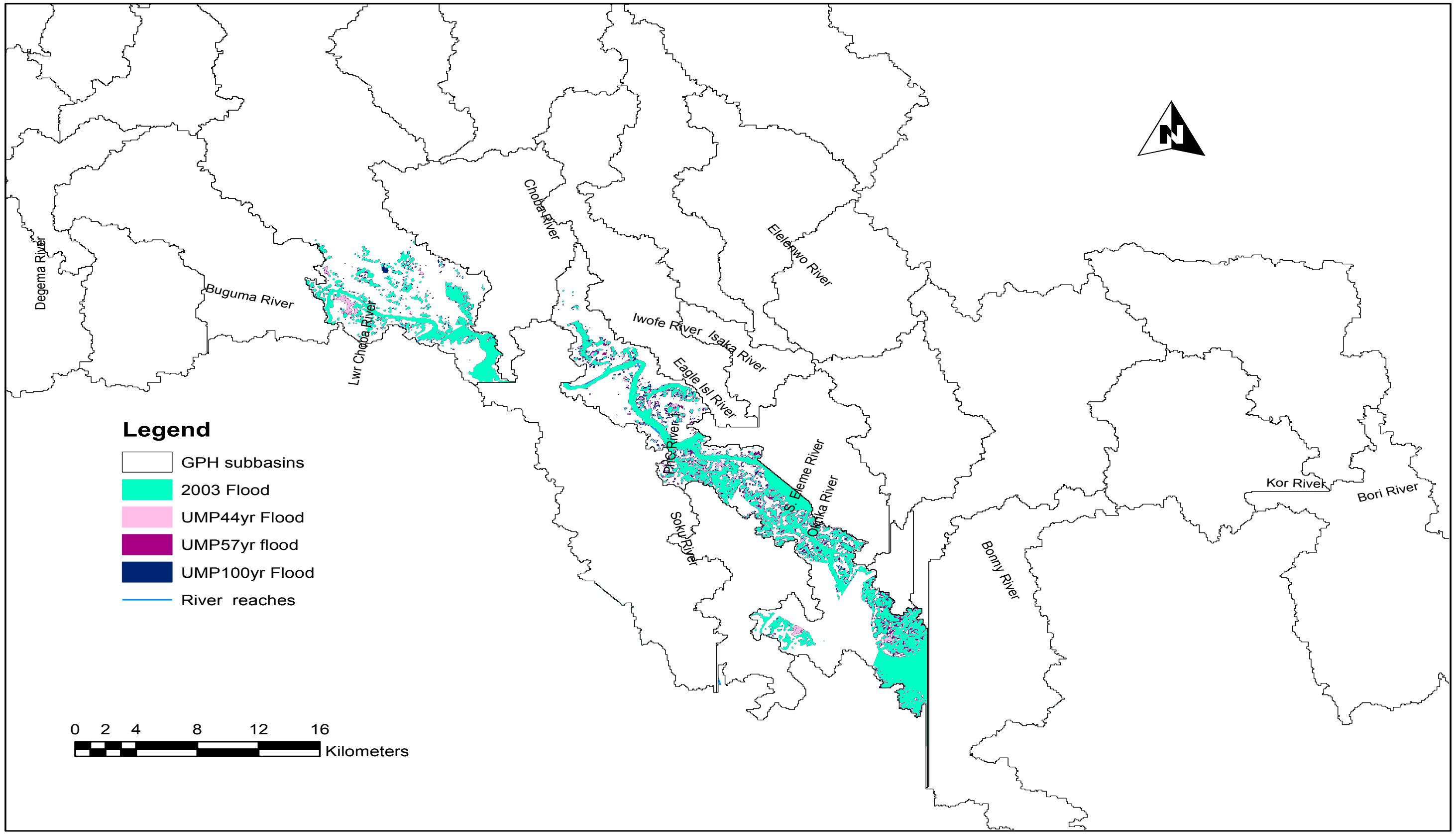

Figure 7.11 Overview map of modelled flood extents for the 2003 historical storm and UMP44yr, UMP57y and UMP100yr Future scenario storms (Scale: 1:300,000).

Figure 7.8 present a 1:300,000 scale overview map of flood extent showing the extent of flooding for all historical events. Figure 7.9 and 7.10 similarly show overview map of flood extent of 1986 and 2003 events respectively. From the estimation, the total flooded area increased from about 293km^2 in 1986 to approximately 338km^2 in 2003, which means flood water spread by an additional 44km^2 in 2003. Regarding future extents, Figure 7.11 display overview maps of potential flood extents based on the future Masterplan and three storm scenarios. Compared to 2003, flood extent is expected to increase to about 338km2 and 358km^2 respectively in the event of 44yr and 57yr storms. That means, flooded areas are likely to expand by 1km^2 and 27km^2 respectively. However, in the event of a UMP100yr storm, approximately, the flooded area is expected to extend by an additional 66km^2. This proves that future storm are projected to inundate more areas than historical storms, as expected. However, there was apparently no change in flood extent due to changes in urban extent. Compared to other flood characteristics such as discharge and flood depth, the maps indicate that flow extent could increase considerably. Moreover, the increase will mainly be due to changes in storm size and not the urban expansion.

7.3.4 Impact on flood velocity

To determine changes in flood velocity in the entire watershed. Analysis of variance was performed to compare velocity means between different scenarios (profiles). Table 7.3 and 7.4 compare means of channel velocity for all scenarios. From the analysis, there was generally no significant difference in mean velocity between the historical and future scenarios. Based on these results, historical changes in channel velocity was insignificant. Similarly, compared to 2003, future changes in channel velocity is likely not to be significant. For all scenarios, p-values were all greater than 0.05. Nonetheless, change between 1986 and the 100yr storm scenarios was significant with a p-value <0.001.

Table 7.3 Multiple comparisons of channel velocity for historical scenarios (P-value all greater than 0.05)

Group Name	N	Mean (m/s)	Std. Dev
1986 (U1)	296	0.273	0.366
1995	296	0.276	0.367
2003	296	0.312	0.399
U2	296	0.270	0.369

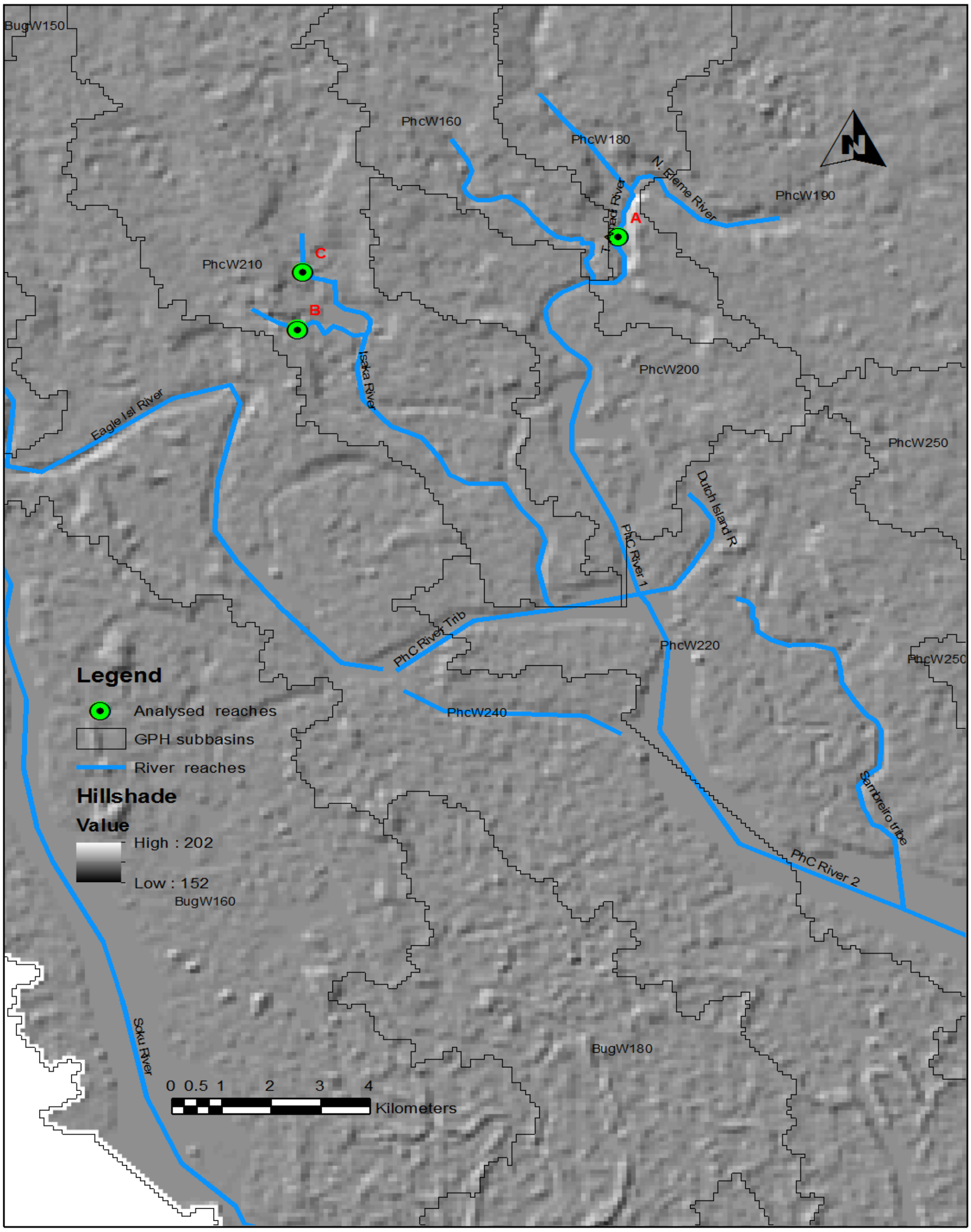

Figure 7.12 Map showing place marks for reaches used for analysing changes in channel velocity. A, B, C, are Trans Amadi, Iwofe, Isaka river (Phc Harbour) reaches respectively.

Table 7.4 Multiple comparisons of channel velocity for 2003 and future scenarios (P-value all greater than 0.05).

Group Name	N	Mean channel velocity	Std. Dev
2003	296	0.312	0.399
UMP44yr	296	0.293	0.389
UMP57yr	296	0.302	0.390
UMP100yr	296	0.325	0.397
UUMP44yr	296	0.292	0.390
UUMP57yr	296	0.302	0.390
UUMP100yr	296	0.330	0.411

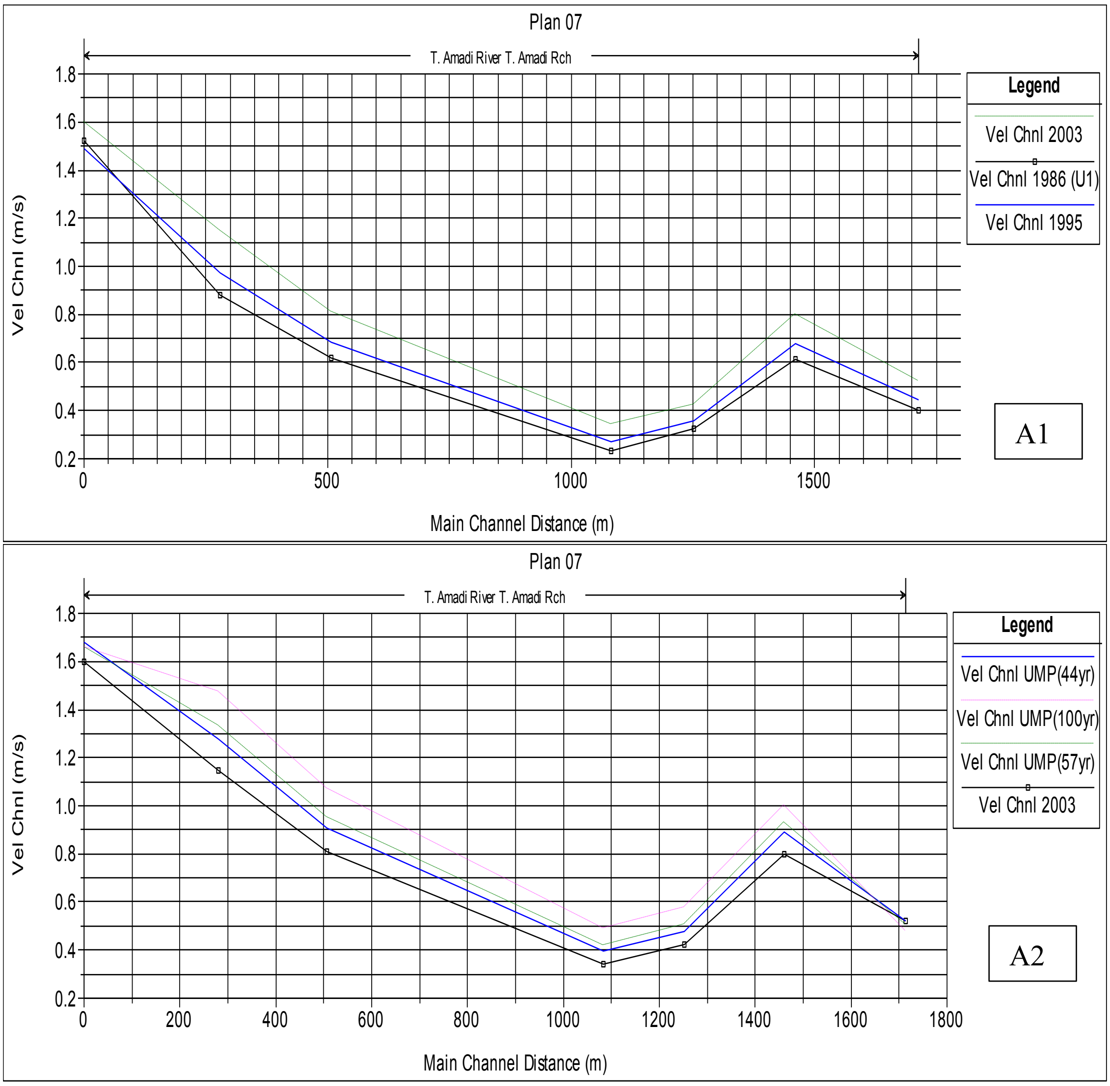

Figure 7.13 Graphs showing longitudinal view of changes in channel velocity along Trans-Amadi reach. A1 show historical changes, while A2 indicate of future changes.

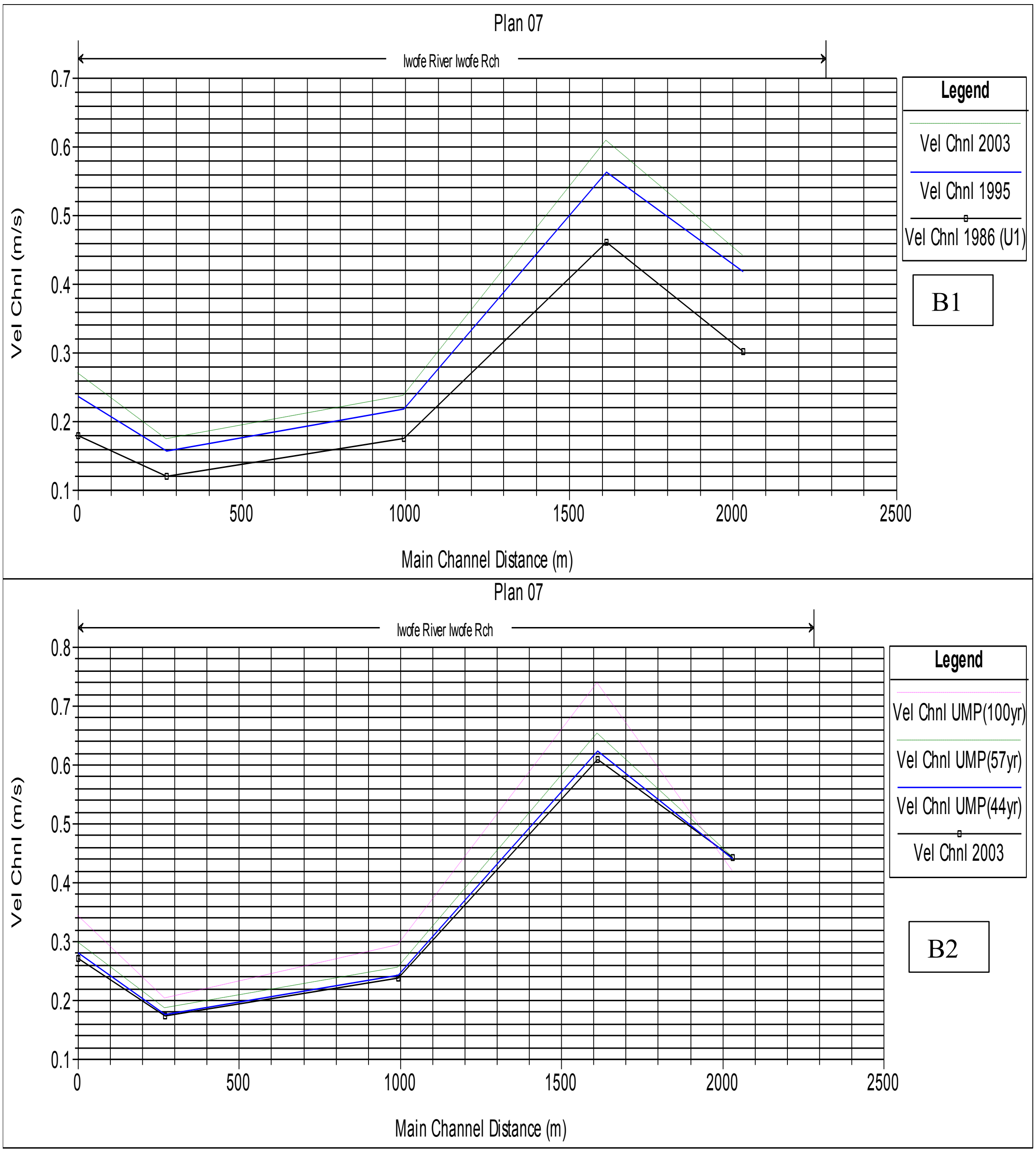

Figure 7.14 Graphs showing longitudinal view of changes in channel velocity along Iwofe reach. B1 show historical changes, while B2 show changes in future.

The map in Figure 7.12 show place marks on three reaches for which flow velocity result are presented. The rivers are located in the eastern and central part of the watershed upstream. Figure 7.13 to 7.17 show longitudinal view of changes in channel velocity of selected upstream reaches. The selected reaches identified with map placemarks in Figure 7.12 above includes the Trans-Amadi reach (A), Iwofe (B), and Isaka reach (near Port-Harcourt Harbour) (C). Plot

1 signifies historical changes and plot 2 signifies potential changes. For example, A1 and A2 (Figure 7.13) are the plots for historical and future changes in channel velocities due to increased storm and urbanisation along the Trans-Amadi reach. A1 indicate that channel velocity increased progressively for most parts of the reach. Channel velocity changed from about 1.52 m/s in the 1986 event to about 1.6 m/s in the 2003 event. Similarly, the second plot (A2) generally show that future flood velocity is likely to be higher than flood velocity in 2003. That is, channel velocity is likely to change from \bout 1.6 m/s in 2003 to about 1.7 m/s in the UMP100yr scenario. For most parts, the maximum channel velocity will result due to the 100yr storm. Both plots show that channel velocity is higher in the downstream areas than in upstream areas for this reach.

Similarly, Figure 7.14 display plot of historical and future changes in channel velocity due to increased storm and urbanisation along the Iwofe reach. The B1 graph indicate that channel velocity increased progressively from about 0.18m/s in 1986 to about 0.28m/s in 2003. Likewise, B2 of the high figure projects that channel velocity will be greater in the future than the in 2003. Similarly, maximum channel velocity is expected to result from 100yr storm. In this case, the difference in channel velocity is slightly higher in the upstream parts of the reach. Similarly, C1 in Figure 7.15 shows that channel velocity along Port-Harcourt Harbour was greater in the 2003 event than in other historical events considered in this study. Meanwhile, C2 demonstrate that channel velocity is likely to be greater in future than in the 2003 due to increased storm.

Plot A3 and B3 in Figure 7.14 show plots of changes in channel velocity due to historical urbanisation. There was generally no obvious change when averaged and considered at the watershed scale, however, Plot A3 show slight changes in channel velocity between (U1 and U2 scenarios) along the Trans-Amadi reach. Channel velocity increased in the downstream part from about 1.52m/s to about 1.57m/s. Similarly, B3 show that slight changes in velocity occurred due to urbanisation along Iwofe reach. The increase in channel velocity was higher in the upstream part (from about 0.30 to about 0.35m/s) than in the downstream region (about 0.18 to about 0.2m/s). However, the majority of the reaches showed no change in channel velocity due to urbanisation (Appendix 7.4). Lastly, data in Appendix 7.4 indicate that changes in channel velocity due to future urbanisation is expected to be less obvious than changes due to historical urbanisation analysed in the study. In a nutshell, changes in velocity were insignificant, and there was little or no change due to urbanisation. Nevertheless, slight changes in channel velocity were observed in two upstream (Tans-Amadi and Iwofe) reaches.

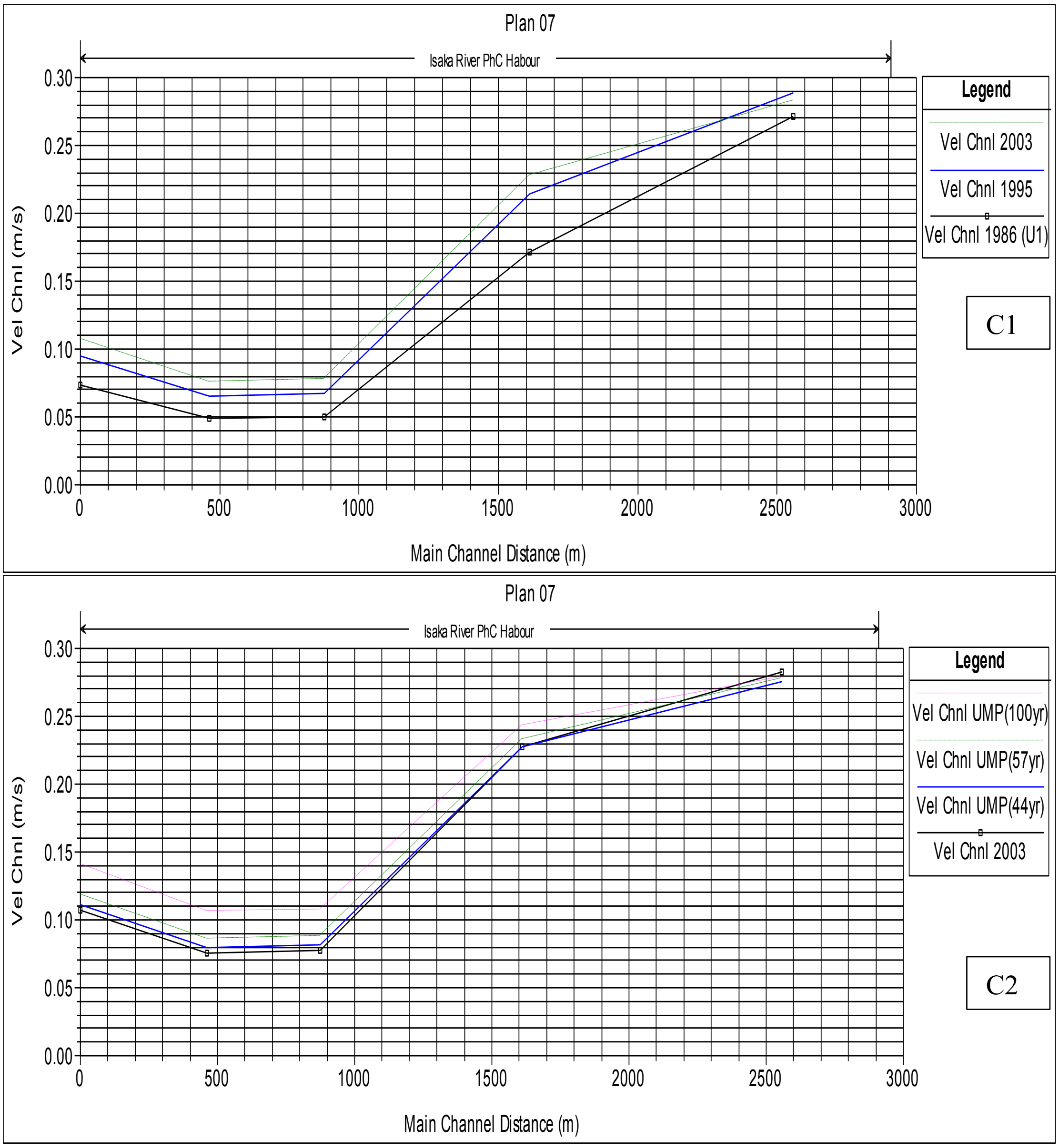

Figure 7.15 Graphs showing longitudinal view of changes in channel velocity along Isaka River (Harbour reach). C1 show historical changes, while A2 indicate of future changes.

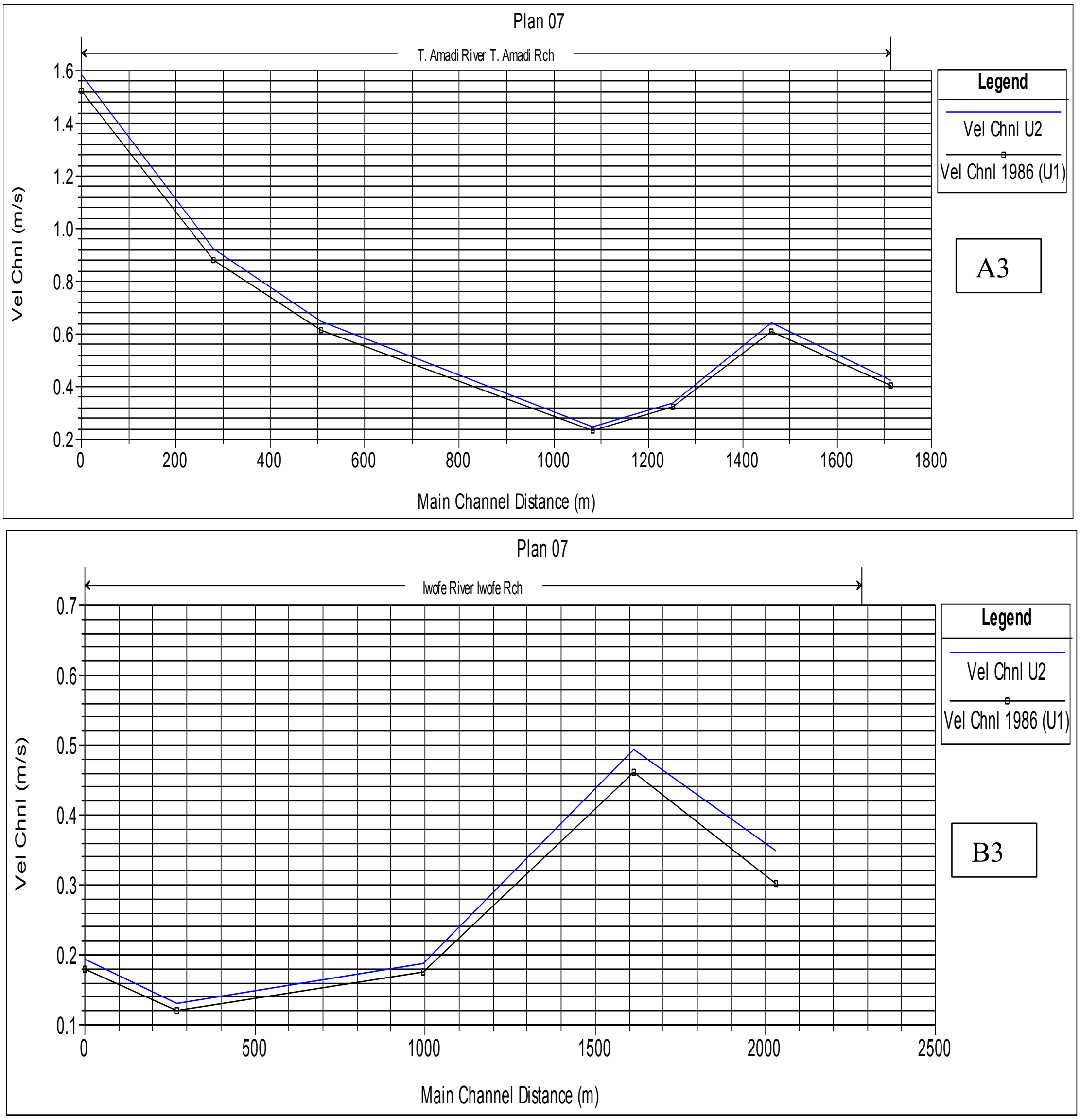

Figure 7.16 Graphs showing longitudinal view of changes in channel velocity along Trans-Amadi reach (A3) and Iwofe reach (B3) respectively due to increased urbanisation. Changes were analysed based on U1 and U2 historical scenarios.

7.4 FLOOD INUNDATION MAPPING RESULT.

7.4.1 Flood Depth.

Flood depth mapping was done to visualise changes in flood depth at different locations in an extreme condition. For this analysis, the flood depth based on 100yr storm flood mapped in Figure 7.17 was overlaid on the 2060 LULC maps (Figured 7.18-7.27). To achieve this, HEC-RAS data was exported into ArcMap and by subtracting water surface from TIN elevation and the flood depth raster maps were derived. Figure 7.17 present a small-scale overview map (1: 500,000) of predicted flood depth across the modelled area for storm return period of 1/100yr, whereas Figure 7.18 to 7.27 present large-scale hazards maps (1:25,000 to 1:60,000) showing predicted flood depth at various locations in the study area. Overall, flood depth varied from about 0 to 23m with the greater depth in the channel. The rating scale used [adopted from Duan *et al.* (2009)] is as follows: flood depth from 0-0.2 meters =Low (1); 0.2-0.5 meters = Moderate (2); 0.5-1.0 meters = High (3) and ＞1.0 meters =Very High (4).

As expected Figure 7.17 indicates that the very high flood depths were found within the river channels. Nonetheless, low to very high flood depths were also observed in flood plains and overbank areas. The maps clearly show that some forestlands, agricultural lands and importantly, urban areas experienced and are likely to experience very high floods in the event of a 100yr storm (see Figure 7.19-7.23). For instance, in the north-western part of the City, Figure 7.18 shows urban areas around the Abua and Egbema area projected to experience floods as high as about 3.7, 6.2 and 6.7m in the different locations. Similarly, urban areas are anticipated to be inundated by flood up to about 5.14 and 2.14m in some parts of the Emohua and Abua (Figure 7.19). Figure 7.23 indicates urban areas around the Elelenwo may be exposed to flood depths up to about 3.12m. In the South, urban areas are likely to be inundated by floods up to 3.6m around the Dutch Island/Okrika area (Figure 7.24). Similarly, in some parts of Bori and Kor areas (south-east of the city), flood inundation is projected to be as high as about 5.1 and 6.5m respectively (Figure 7.26 and 7.27). Urban and agricultural lands located in the north-west and south-eastern part of the city are likely to experience higher floods.

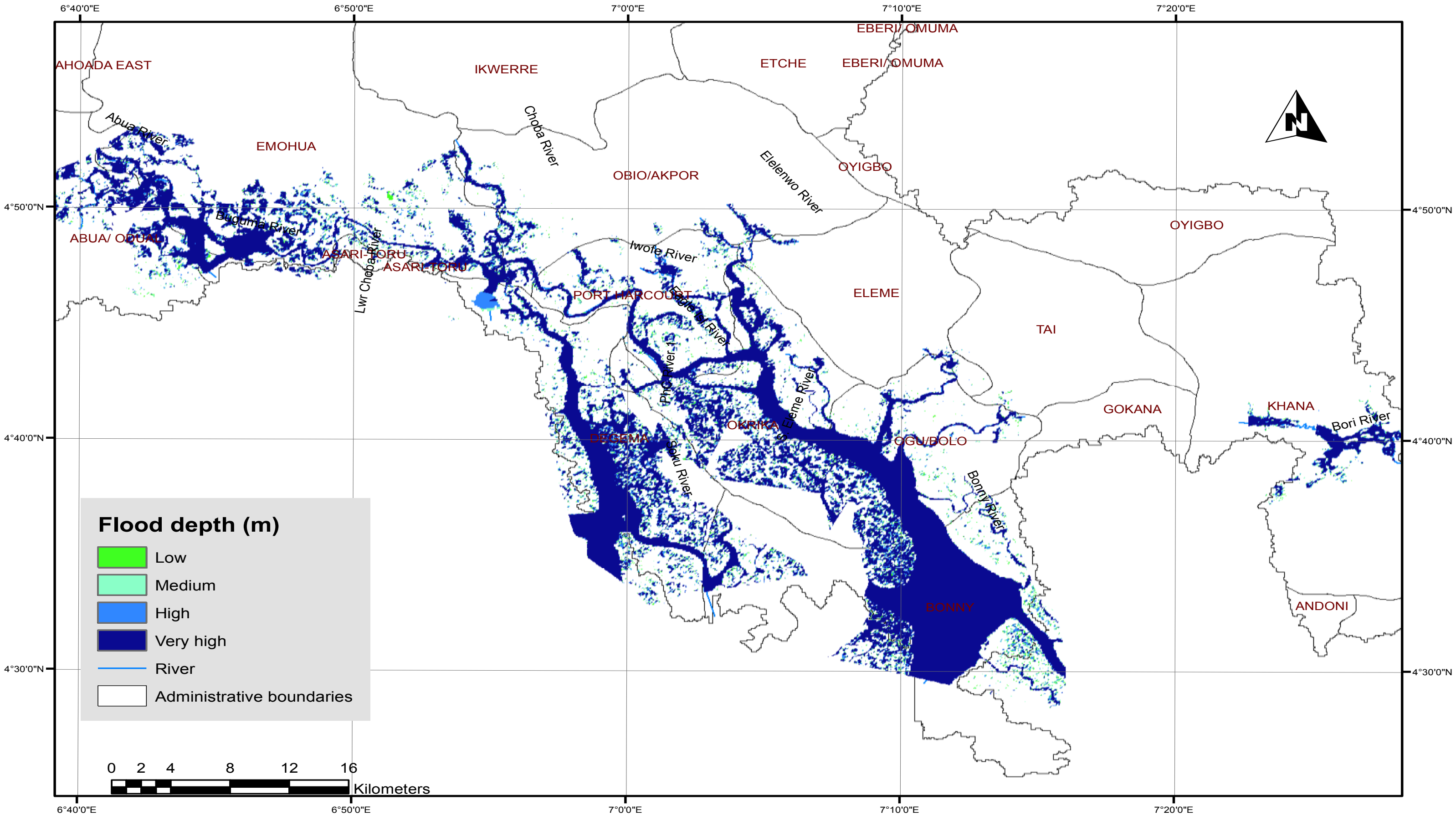

Figure 7.17 Overview flood depth map for the 100yr-storm flood covering the entire modelled area of Greater Port-Harcourt watershed. Map scale =1:500,000.

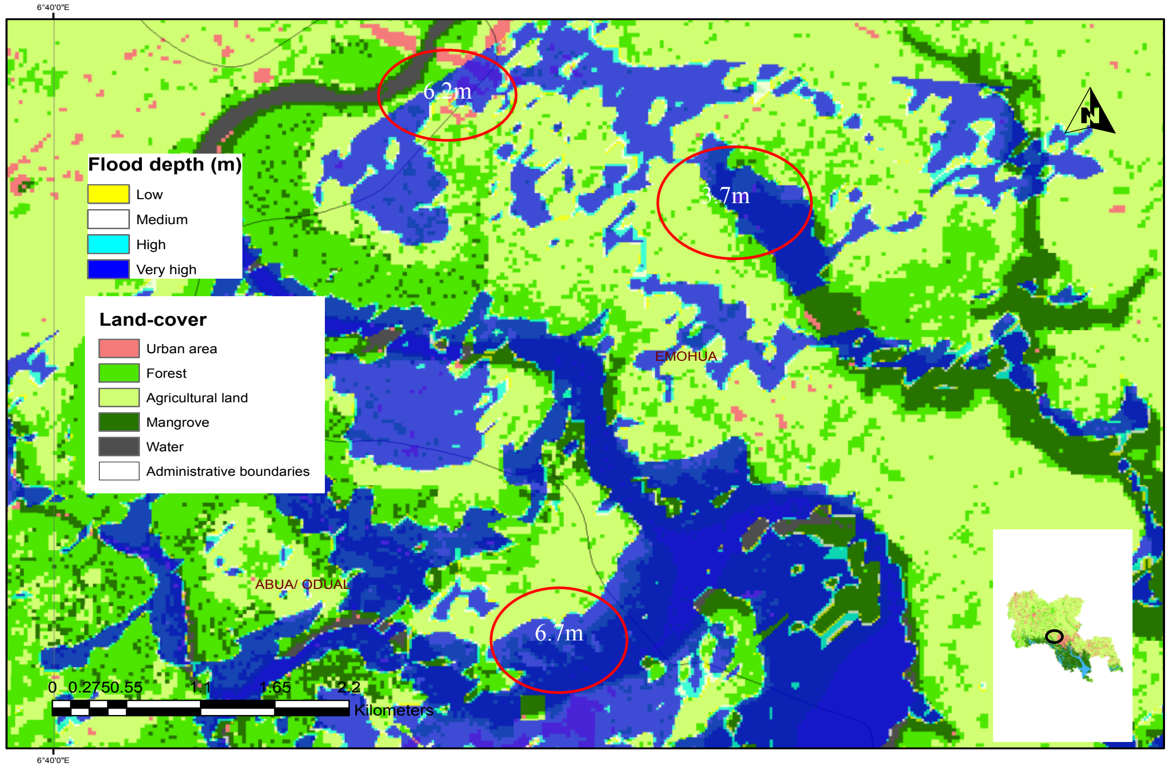

Figure 7.18. Flood depth map for the Abua /Egbema area in Greater Port-Harcourt for 100yr storm return period.

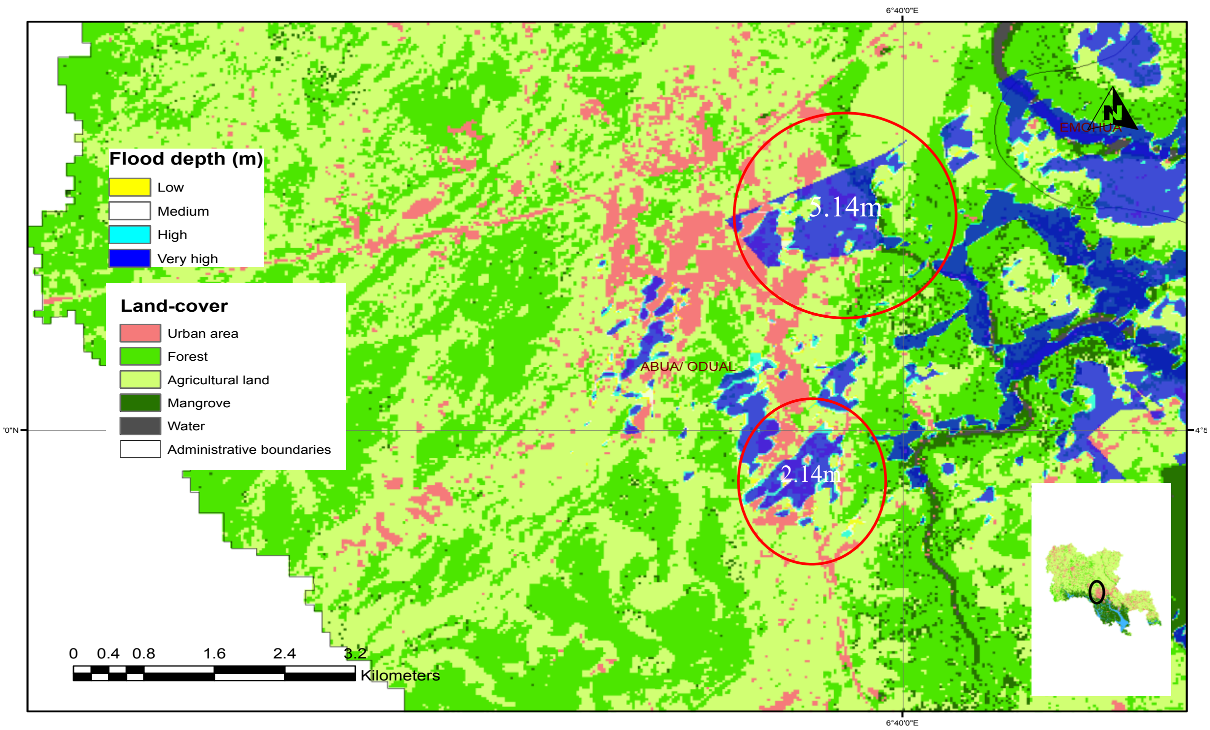

Figure 7.19 Flood depth map covering Emohua, Abua/Odual area in Greater Port-Harcourt for 100yr storm return period

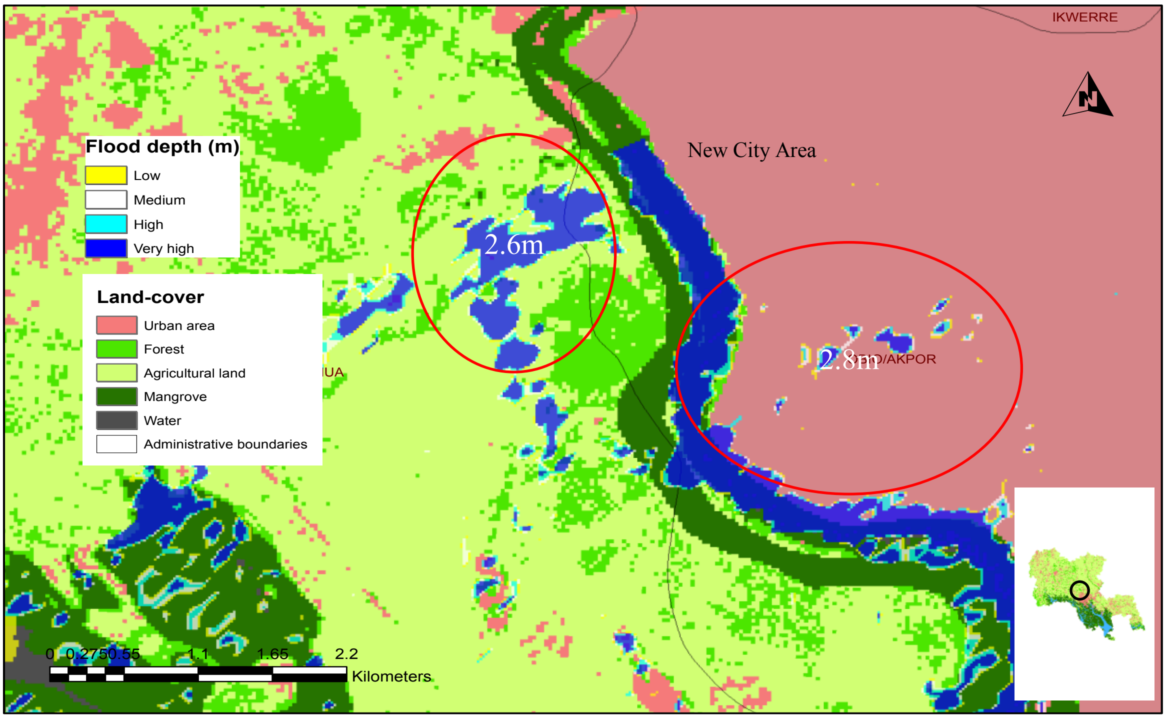

Figure 7.20 Flood depth map covering Choba area in Greater Port-Harcourt for 100yr storm return period.

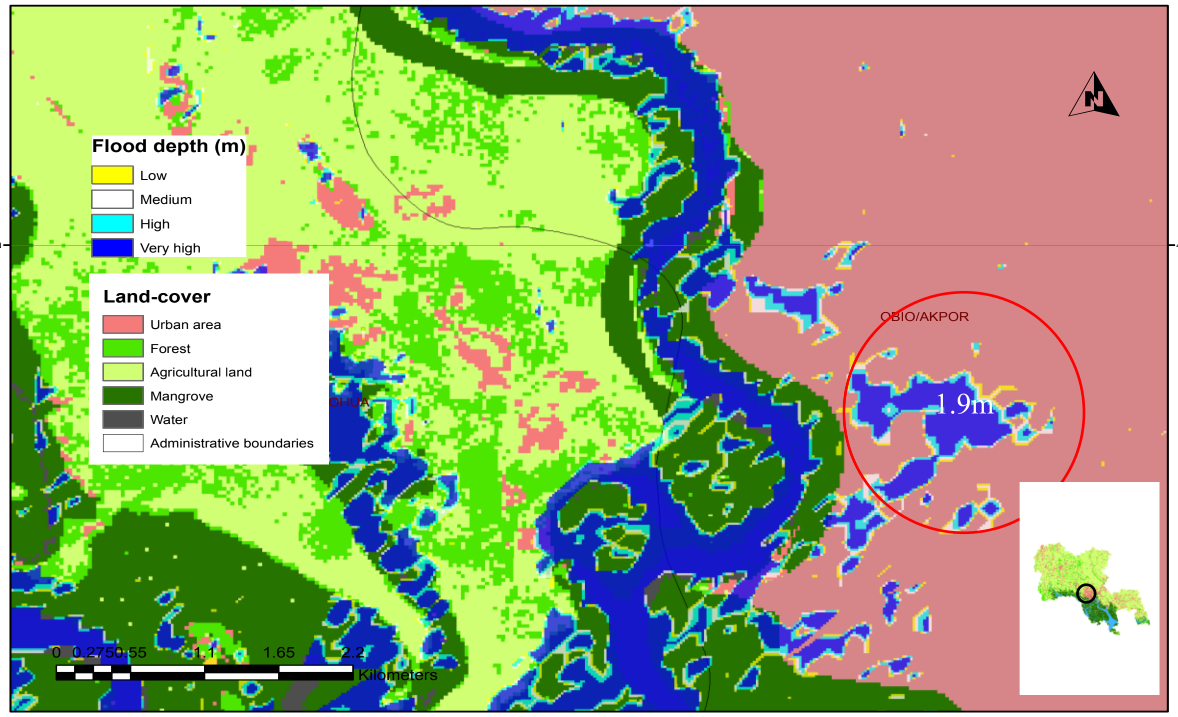

Figure 7.21 Flood depth map covering Eagle Island area in Greater Port-Harcourt for 100yr storm return period.

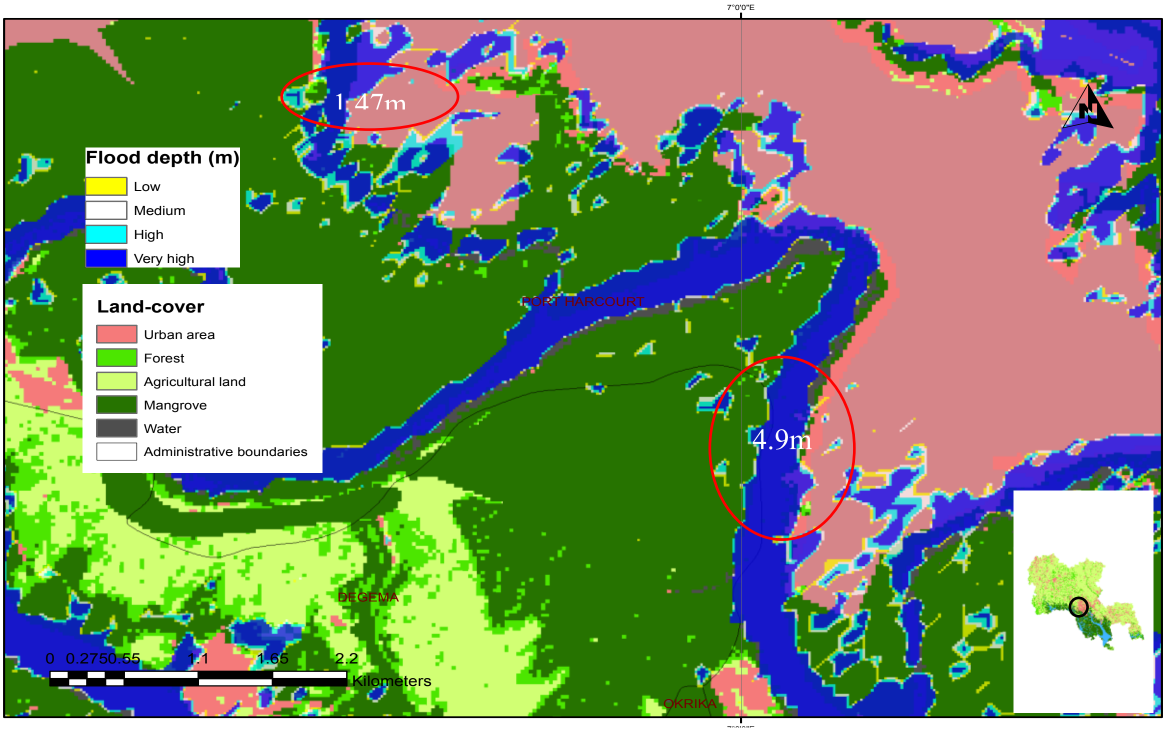

Figure 7.22 Flood depth map around Southwest of Obio/Apko area in Greater Port-Harcourt for 100yr storm return period.

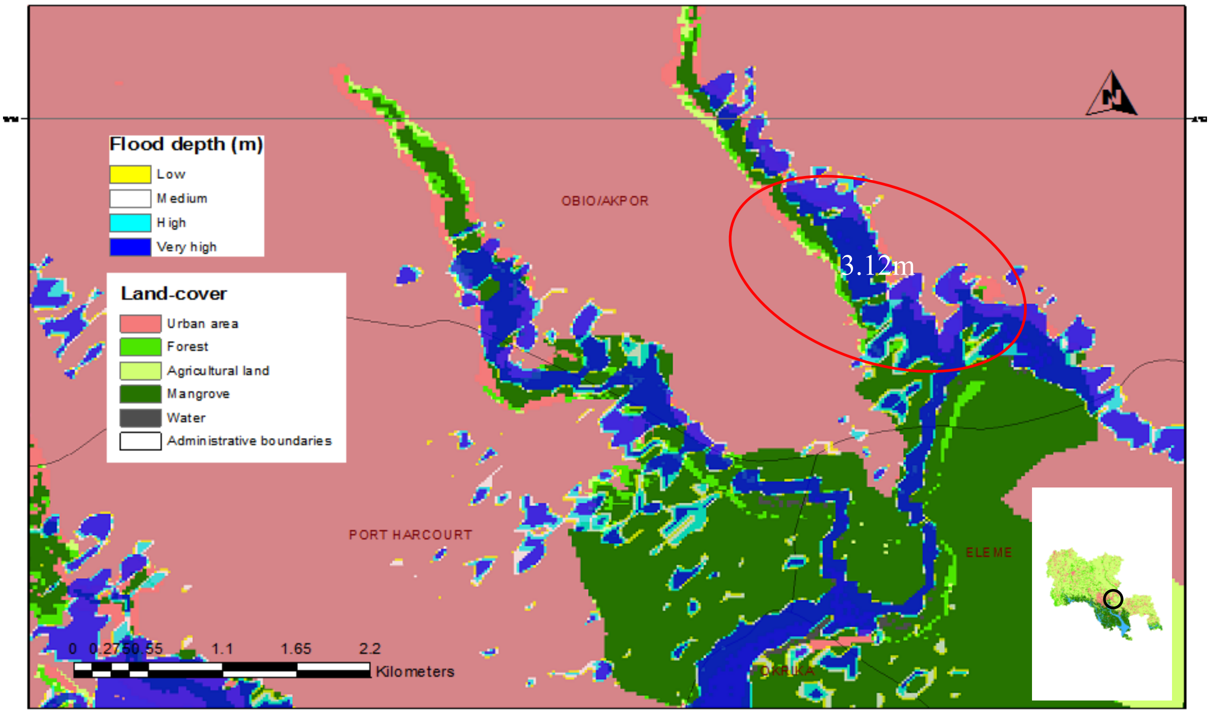

Figure 7.23 Flood depth map around North Eleme and Elelenwo area in Greater Port-Harcourt for 100yr storm return period.

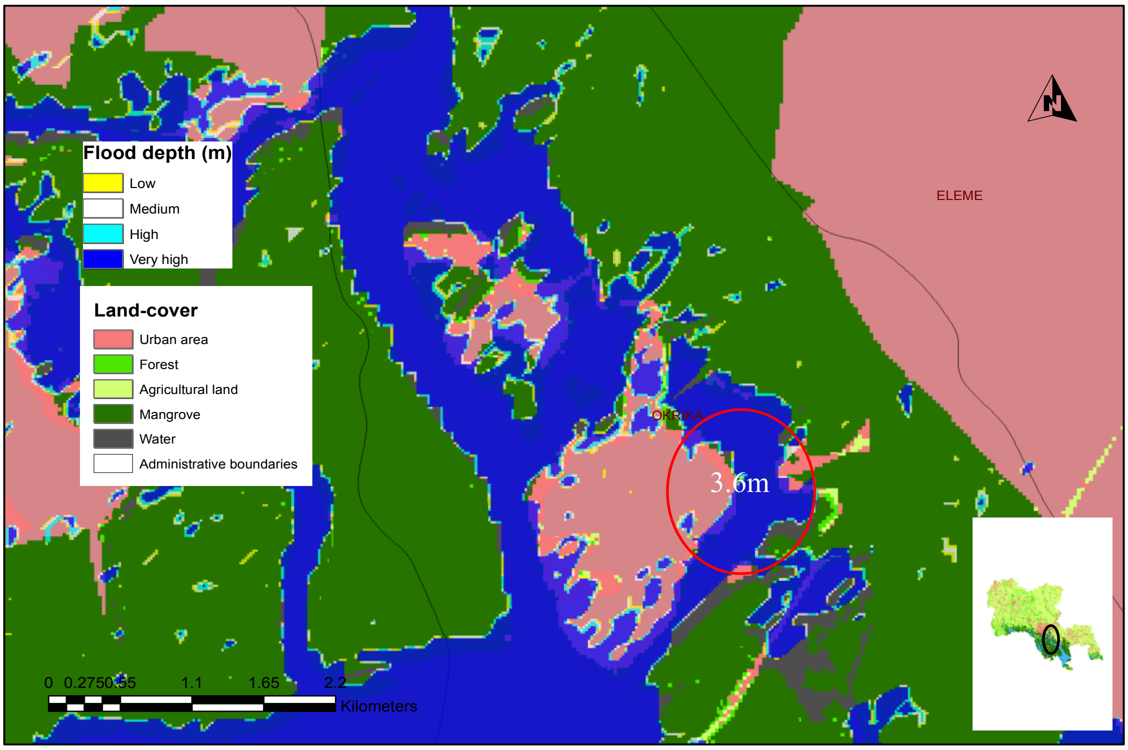

Figure 7.24 Flood depth map around Dutch Island/Okrika area in Greater Port-Harcourt for 100yr storm return period.

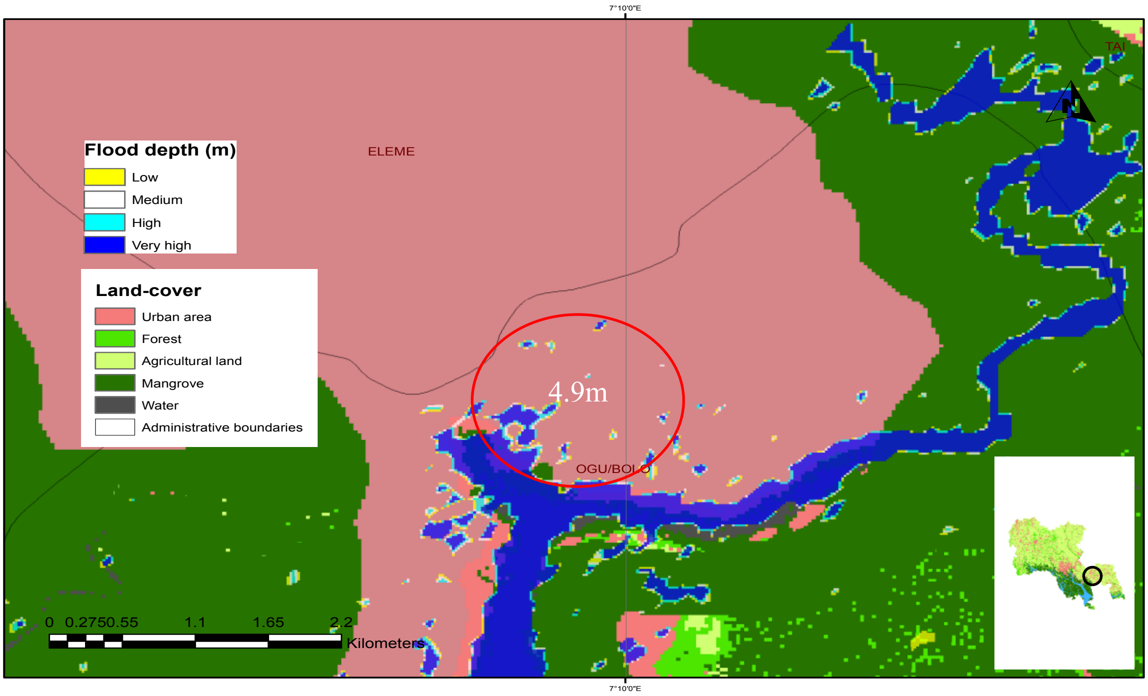

Figure 7.25 Flood depth map around South Eleme and Ogubolo area in Greater Port-Harcourt for 100yr storm return period.

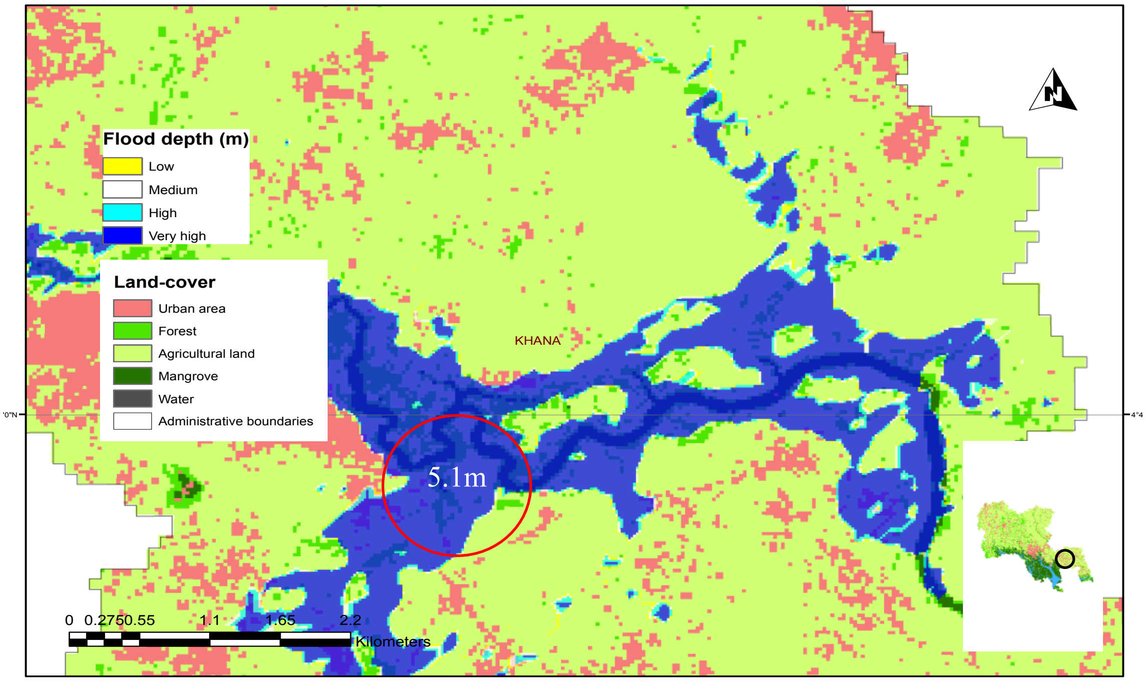

Figure 7.27 Flood depth map around Khana area (along Bori River) in Greater Port-Harcourt for 100yr storm return period.

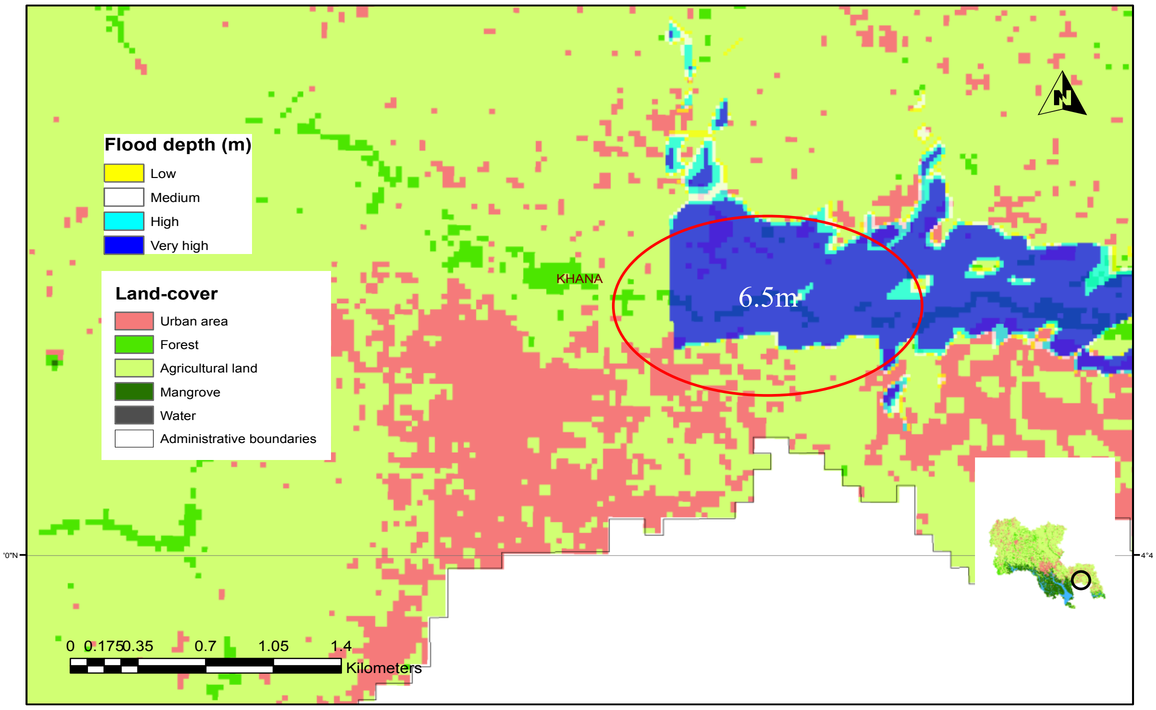

Figure 7.26 Flood depth map around Khana area (along Kor River) in Greater Port-Harcourt for 100yr storm return period.

7.4.2 Flood Zone Mapping.

Flood extent maps were further used to construct flood zones maps for the watershed. The flood zone maps show graphical information of expected floods due to storms based on of 2.5yr, 38yr and 100yr return periods. Categorised as Low, Medium and High probabilities, the 2.5yr, 38yr and 100yr storm floods were based on 1986, 2003 and UMP100yr storm flood scenarios respectively. The maps were primarily used to designate zones that could be flooded in the event of storms of the above probabilities. The shaded areas presented in the maps align with the flood zones defined by:

- Zone 1-Low probability (shaded blue), represent areas that could be flooded due to extreme (or low frequency) storm with an annual probability of 1% (1 in 100).
- Zone 2-Medium probability (shaded yellow), represent areas that could be flooded due to moderate (or medium frequency) storm with annual probability equal to 2.6 % (1 in 38).
- Zone 3-Low probability (shaded red), represent areas that could be flooded due to a smaller storm (high frequency) with an annual probability equal to or greater than 40% (1/2.5).

Figure 7.28 to 7.34 present flood zones maps of seven selected districts in the watershed. The chosen locations were analysed due to the presence of residential and commercial buildings in the area, because risk to people and infrastructure is pertinent to this research. Generally, from observation, about 2618 buildings fall under all zones in the maps analysed. In the old Port-Harcourt Township district alone (Figure 7.28), Zone 1 (shaded blue) covers the smallest extent, and about 149 buildings are located in this low probability zone. 99 buildings are located in Zone 2 (the medium probability zone), while 789 buildings are located in Zone 3 (the high probability zone). In contrast, in the Borokiri district (Figure 7.29), more building are found in Zone 1, while fewer (49) buildings are found in Zone 3. The least number of building (40) are located in Zone 2.

Likewise, in the Abo Ama district, 86 buildings are located in zone 1, 65 buildings in Zone 3 and 57 in Zone 2 (Table 7.5). Compared to the Borokiri district and Abo Ama districts, more buildings are located in Zone 1 in the Eastern old industrial layout area, Eagle Island and Abonnema Wharf districts. In addition, flood extents in the three zones were measured for the Abonnema Wharf district (Figure 7.34). It indicates that flood extent in Zone 1 (779m) is greater than the flood extent in zone 2 (506m) and Zone 3 (455m) respectively. Like in many areas, it demonstrates that the 1 in 100yr storm flood may encroach into built up areas. In terms of the urban areas covered by flood zones, Table 7.5b shows about 20km^2 of urban areas in 2060 will be affected by 100yr flooding, compared to about 9% to be affected by 2.5 floods.

Table 7.5 Net number of building under the three Flood Zones (1, 2, 3) in maps analysed. Flood zones are based on Low, Medium and High probability storm floods. Buildings are majorly residential, but includes some commercial buildings as well.

S/N	Districts	Figure	Zone 1	Zone 2	Zone 3	Total in each district
1	Old Port-Harcourt Township area	Figure 7.28	149	99	789	888
2	Borokiri Area	Figure 7.29	204	40	49	293
3	Abo Ama	Figure 7.30	86	57	65	208
4	Eastern Industrial layout	Figure 7.31	313	8	133	454
5	Ogubolo	Figure 7.32	72	37	129	238
6	Eagle Island	Figure 7.33	93	18	2	113
7	Abonemma wharf	Figure 7.34	187	60	28	275
	Total in Zone1, 2 and 3		1104	319	1195	2618

Table 7.6 Gross extent of the urban area potentially affected by Low, Medium and High probability storm floods in 2060.

Probabilities	Urban area under zone (km^2)
1in 2.5	8.9
1 in 38yr	12.7
1 in 100yr	19.6

Generally, for the areas analysed, Table 7.5 indicates that more buildings are located in high and low probability zones than the medium probability zone. From Table 7.5 it can be seen that more number of buildings are vulnerable to zone 3 floods which is the area with the highest priority. Specifically, about 1104 building are likely to be affected by a 2.5yr storm flood in the areas analysed. Table 7.6 shows that more urban area (about 20%) could be exposed to 100yr storm floods in 2060.

Figure 7.28 Flood hazard zones defined for part of Old Port-Harcourt Township district. Zone 1=1/100yr storm flood; zone =1/38yr storm flood; zone 3 =1/2.5yr storm flood.

Figure 7.29 Flood hazard zones for part of the Borokiri district in the Old city. zone 1=1/100yr storm flood ; zone =1/38yr storm flood; zone 3 =1/2.5yr storm flood.

Figure 7.30 Flood zones defined for part of Abo Ama district. Zone 1=1/100yr storm flood; zone =1/38yr storm flood; zone 3 =1/2.5yr storm flood.

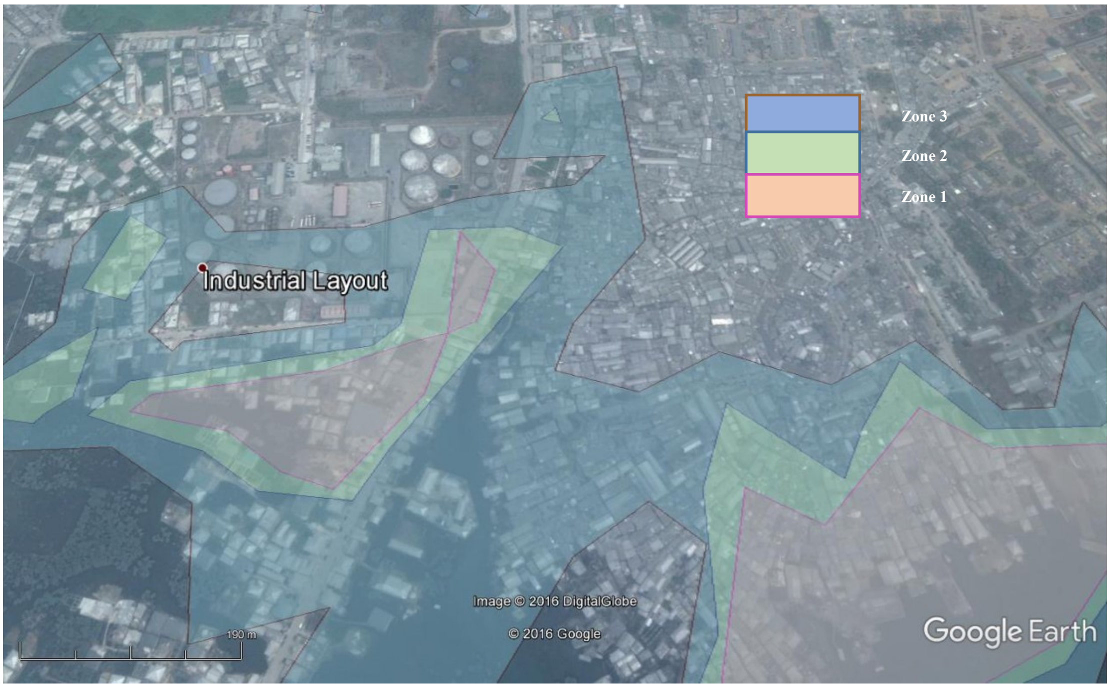

Figure 7.31 Flood hazard zones defined for part of the Port-Harcourt East industrial layout district in the Old City. zone 1=1/100yr storm flood ; zone =1/38yr storm flood; zone 3 =1/2.5yr storm flood.

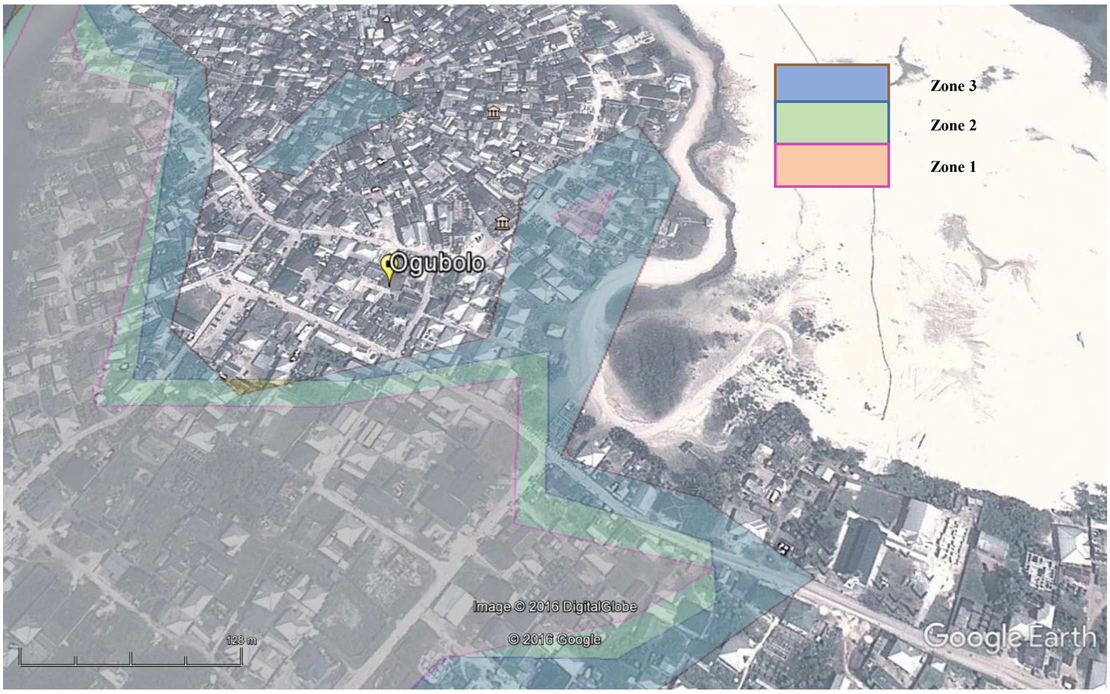

Figure 7.33 Flood hazard zones defined for part of the Ogubolo area (near Okrika) south east of the Old City. zone 1=1/100yr storm flood ; zone =1/38yr storm flood; zone 3 =1/2.5yr storm flood.

Figure 7.32 Flood zones defined for part of the Eagle Island area in the Old City. zone 1=1/100yr storm flood ; zone =1/38yr storm flood; zone 3 =1/2.5yr storm flood.

Figure 7.34 Flood zones defined for the Port-Harcourt Harbour/Abonnema Wharf area in the Old City. Lines indicate flood extent (in meter) in the three Zones. zone 1=1/100yr storm flood ; zone =1/38yr storm flood; zone 3 =1/2.5yr storm flood.

7.4.3 Flood Damage potential.

RAS model output was also used to rate flood hazard for the 100yr (low probability flood zone) watershed. The flood danger maps indicate potential danger, associated with 100yr storm flood. According to Van Alphen *et al.* (2007), it provides an assessment of the direct risk to life arising from the combination of water depth and its velocity of flow based on experiments. The calculation of flood hazard performed with raster calculator in ArcMap environment builds upon the mathematical formula: HR = d x (v + 0.5) + DF. The formula takes into account the depth (d) and velocity (v) of floodwaters as well as debris factor (DF=0.5) to provide a flood hazard rating value. Debris factor was integrated based on the assumption that debris-filled flowing water increases the danger to people, see Van Alphen *et al.* (2007). Figure 7.35 present a velocity map derived by interpolating model output using the kriging method (Gaussian process). Interpolation was done to create a 2-D velocity map prior to the danger mapping.

Table 7.6 showing flood hazard values, rating and the degree of flooding given as function of water depth and velocity of flow and debris factor. Flood hazard maps indicate the hazard, or potential danger associated with the 100yr storm flood.

Hazard rating value d x (v + 0.5) + DF	Flood hazard category	Description of the potential danger to people
<0.75	Low	Caution "Flood zone with shallow flowing water or deep standing water."
0.75 – 1.25	Moderate	Dangerous for some (i.e. children)"Danger: Flood zone with deep or fast flowing water."
1.25 – 2.5	Significant (High)	Dangerous for most people "Danger: flood zone with deep fast flowing water."
>2.5	Extreme (Very high)	Dangerous for all "Extreme danger: flood zone with deep fast flowing water"

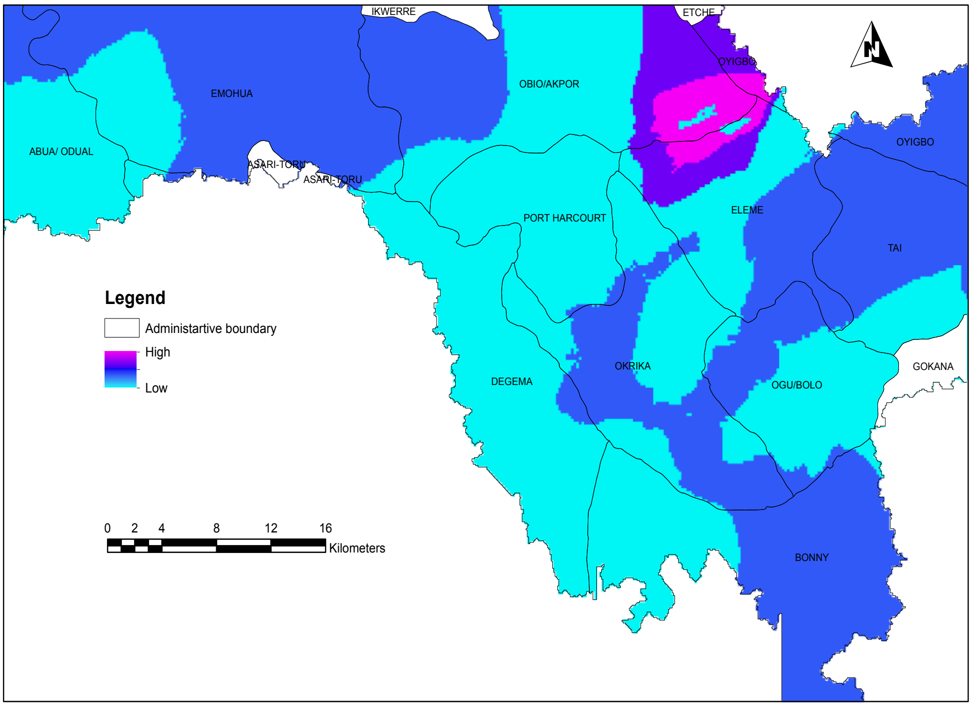

Figure 7.35 Velocity map of 100yr storm flood derived by interpolating RAS model data. Interpolation of 1-D line (to point) data was performed using kriging method or the Gaussian process in ArcMap.

To identify the priority areas and infrastructure at risk to flooding based on their exposure to high flood hazards, important infrastructure and roads around the coast were mapped. Figure 7.36 present the overview map of flood hazard indicating levels of potential danger in the modelled area. Generally, low to moderate floods are predicted to occur outside the flood channel area, as expected, the extremely dangerous flood with deep fast flowing is likely to occur within flood channels, nevertheless, this category of flood will not be limited to flood channels but prone to occur in upstream areas including residential and industrial areas where most people live. Figure 7.37 show that important infrastructure could to be exposed to very high hazard. It indicates critical infrastructure such as seaports (3), cement factory (1), military base (1), and the university area are likely going to be affected. In the south-east, the proposed residential areas in the Masterplan are also expected to be affected. Other elements include seaport storage tanks and seaport installations.

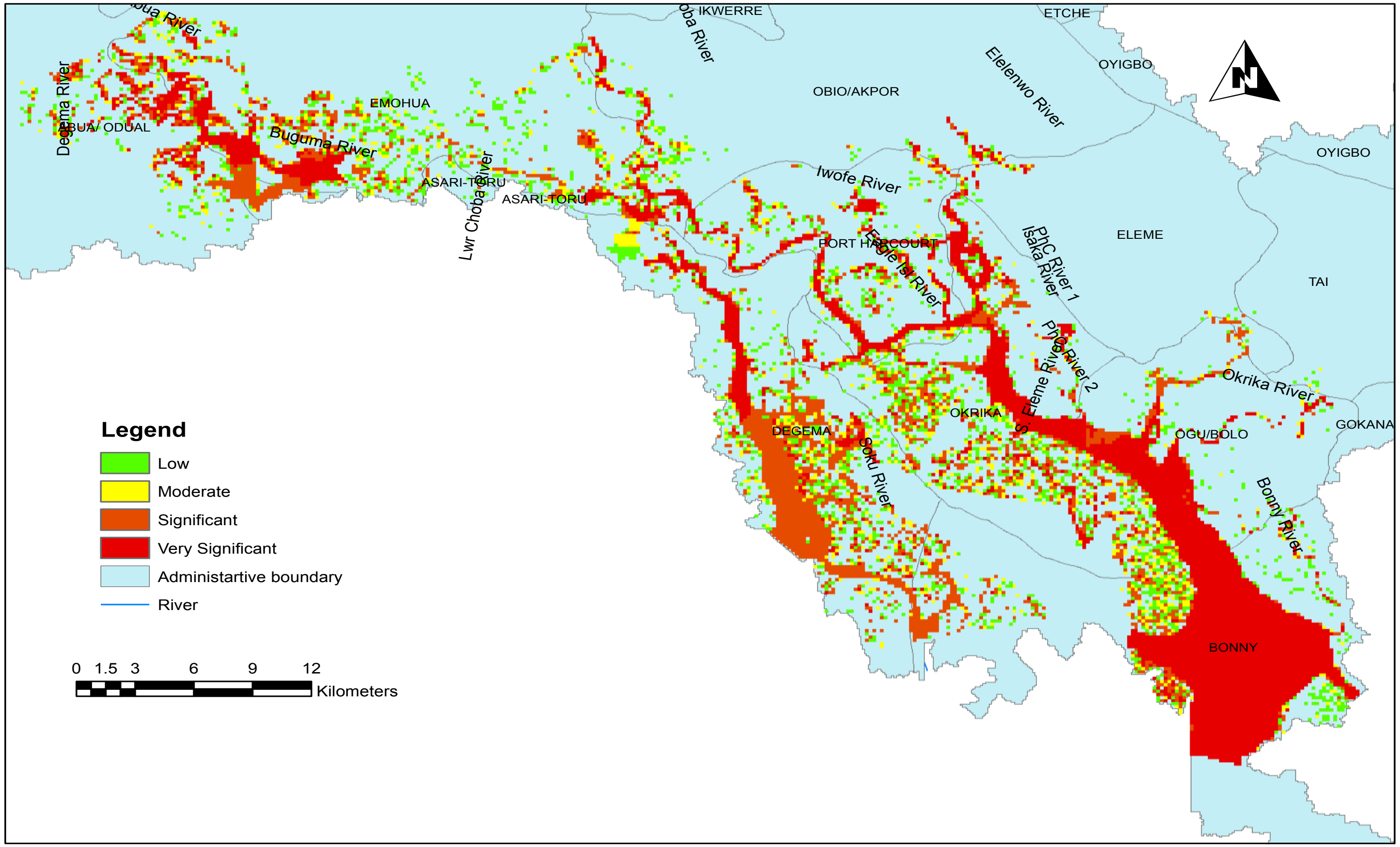

Figure 7.36 Overview map of Flood hazard for the modelled area in GPH watershed.

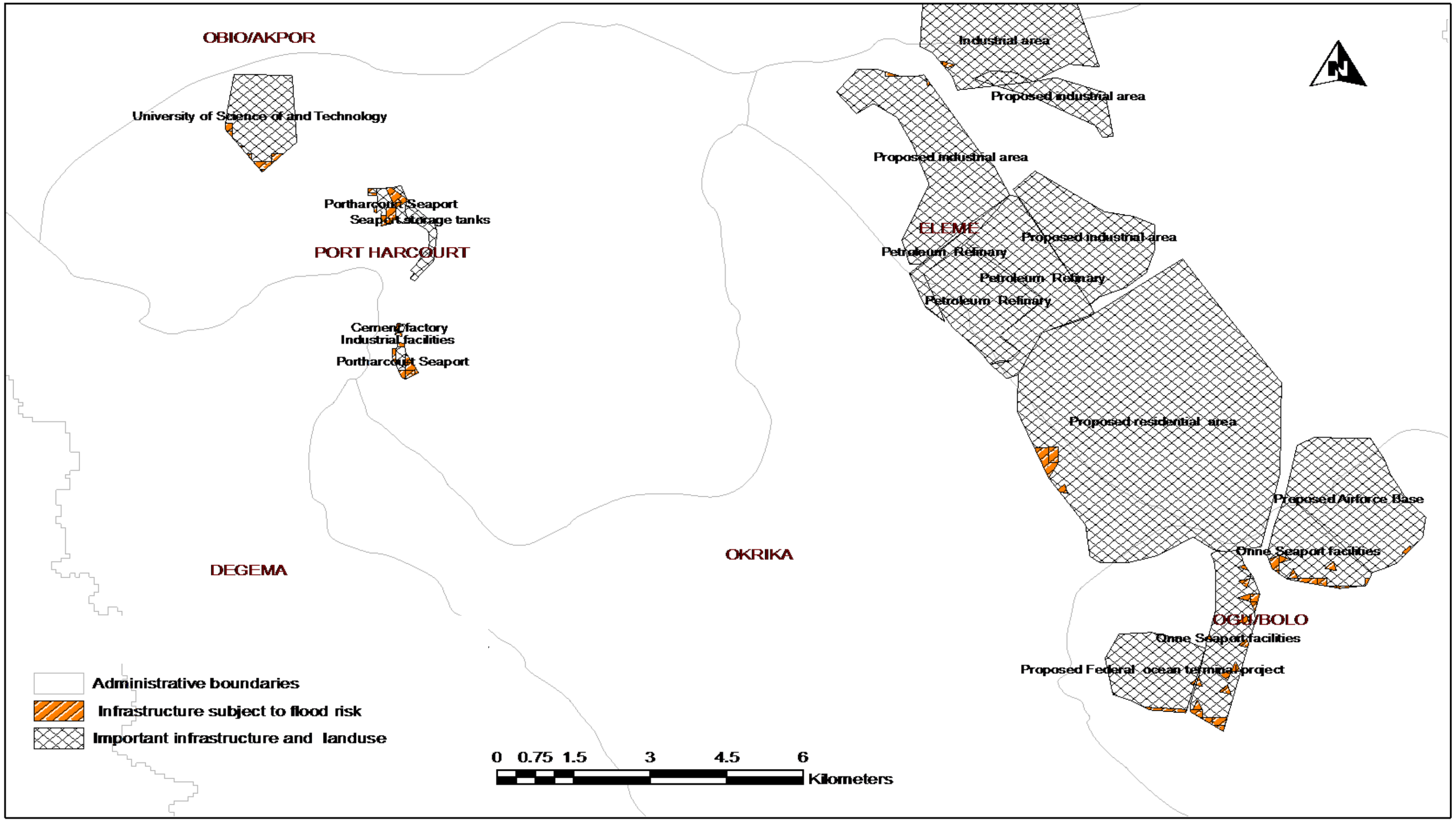

Figure 7.37 Map showing important infrastructure and areas at risk by means of flood depth, flood velocity (integrated with debris factor).

It indicates that one cement factory, three seaports, part of the University and part of the newly planned Air force base are at risk to future flooding.

Table 7.7 Area of infrastructure potentially at risk to flooding.

Important infrastructure/area	Hectare
Onne Seaport	1.9
University	12.7
Airforce base	1.5
Phc Seaport 1	13.6
Industrial facilities	0.9
Phc Seaport 2	21.9
FOT	6.4
Proposed industrial area	25.8
Cement factory	0.8

From the Table 7.8 above, approximately 2, 13 and 21 hectares of the Onne, Port-Harcourt Seaports 1 and 2 are projected to be affected. About 12 hectares of the University of Science and Technology is likely to be affected. Moreover, about One hectare of the cement factory is likely to be exposed the flood hazard. Appendix 7.6 show that about 248 buildings in Figures 7.41-7.46 are likely subject to very high hazard, i.e. to deep and fast flowing floods

Figures 7.38 to 7.40 show important roads and rail network at risk of flooding by means of their exposure to flood depth and flood velocity (including debris factor). From the analysis, it was estimated that 37.1km (out of 1011km of roads mapped) is likely to be affected due to exposure to flood hazard. Of the 37.1km of roads to be affected, Table 7.8 indicate about 50% (19.2 km) of the roads could be exposed to high and very high hazard. About 11.1 km (30%) of the potentially affected roads are likely to lie in high flood hazard areas, while as much as 8.1 km (about 21%) of the roads analysed could lie under very high flood hazard. Similarly, from the 61.0 km of the rail network mapped, Figure 7.40 indicate that about 189m of the rail line is likely to be affected in future. Moreover, all affected part of the rail could be exposed to very high floods. From the road map, major haulage route such as the east-west road from Bori to Port-Harcourt routes are expected to be affected. The majority of the affected roads are located in south, south-east and south-west of Port-Harcourt city.

Table 7.8 Length of road exposed to different hazard categories

Length of road in Km	Hazard category	Grid code
12.1	Low	1
5.8	Moderate	2
11.1	High	3
8.1	Very high	4

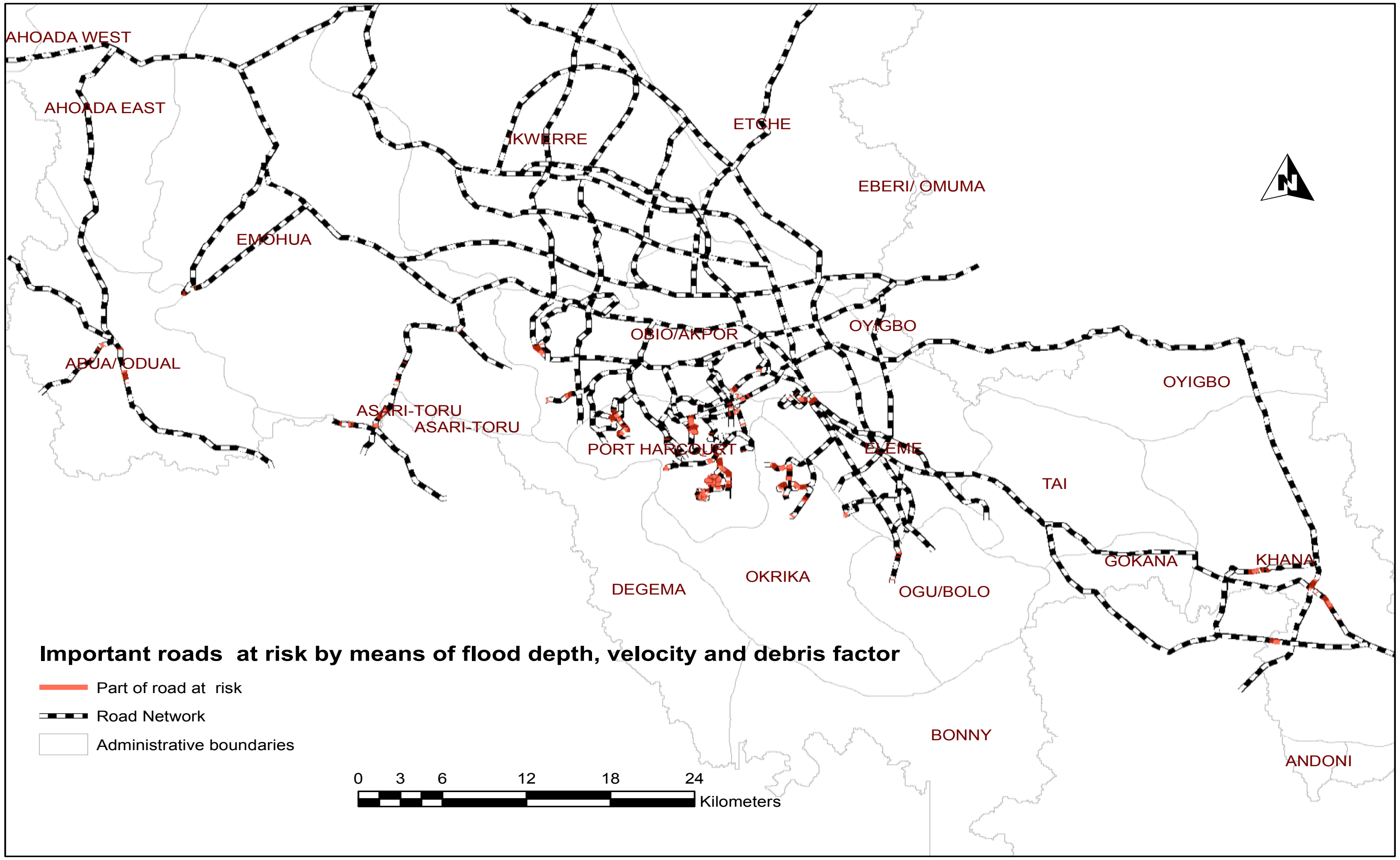

Figure 7.38 Overview map showing important roads at risk to flooding by means of their exposure flood depth and flood velocity (including debris factor). From the map, 37km of road are at risk to flooding.

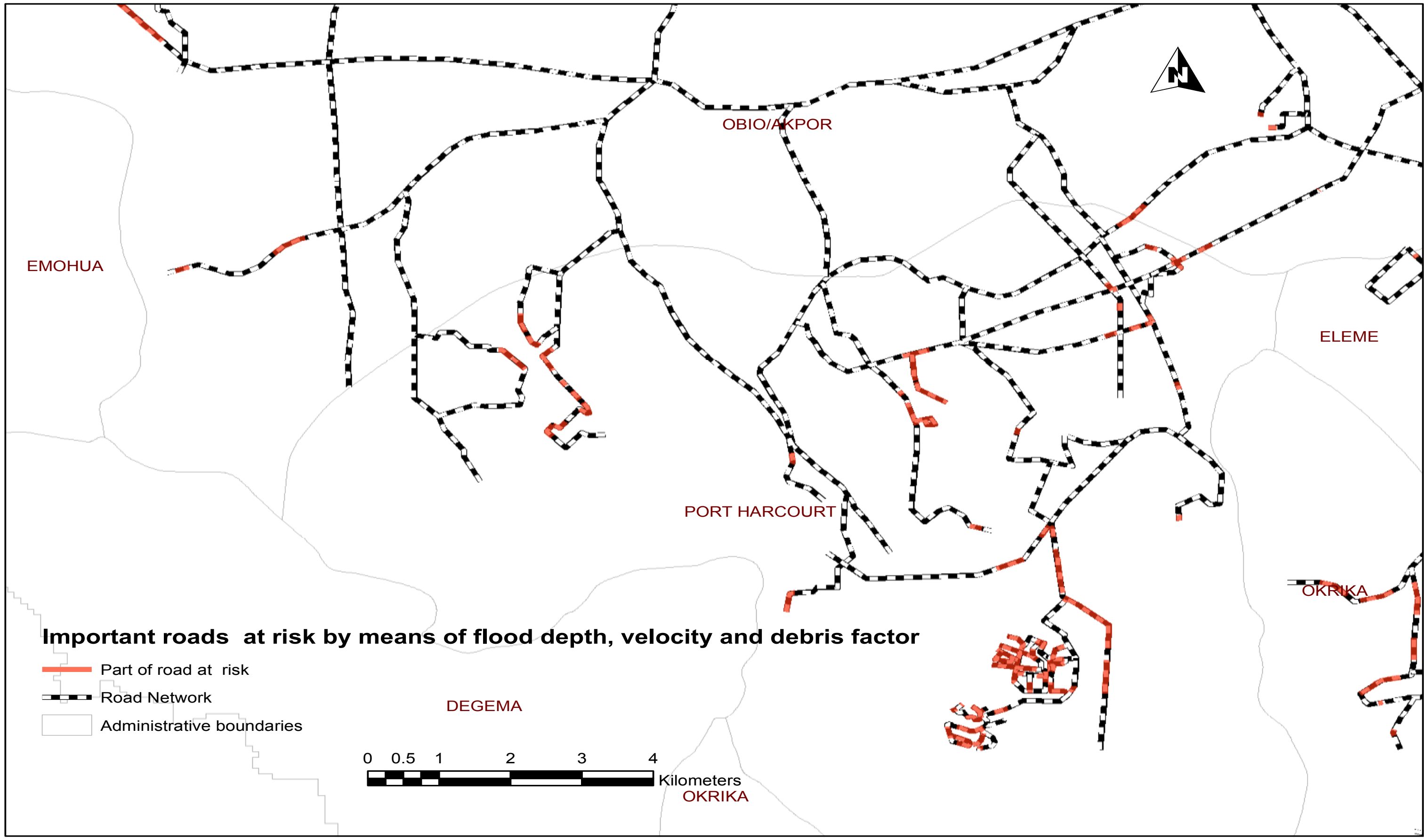

Figure 7.39 Map showing important roads at risk to flooding by means of flood depth and flood velocity (including debris factor).

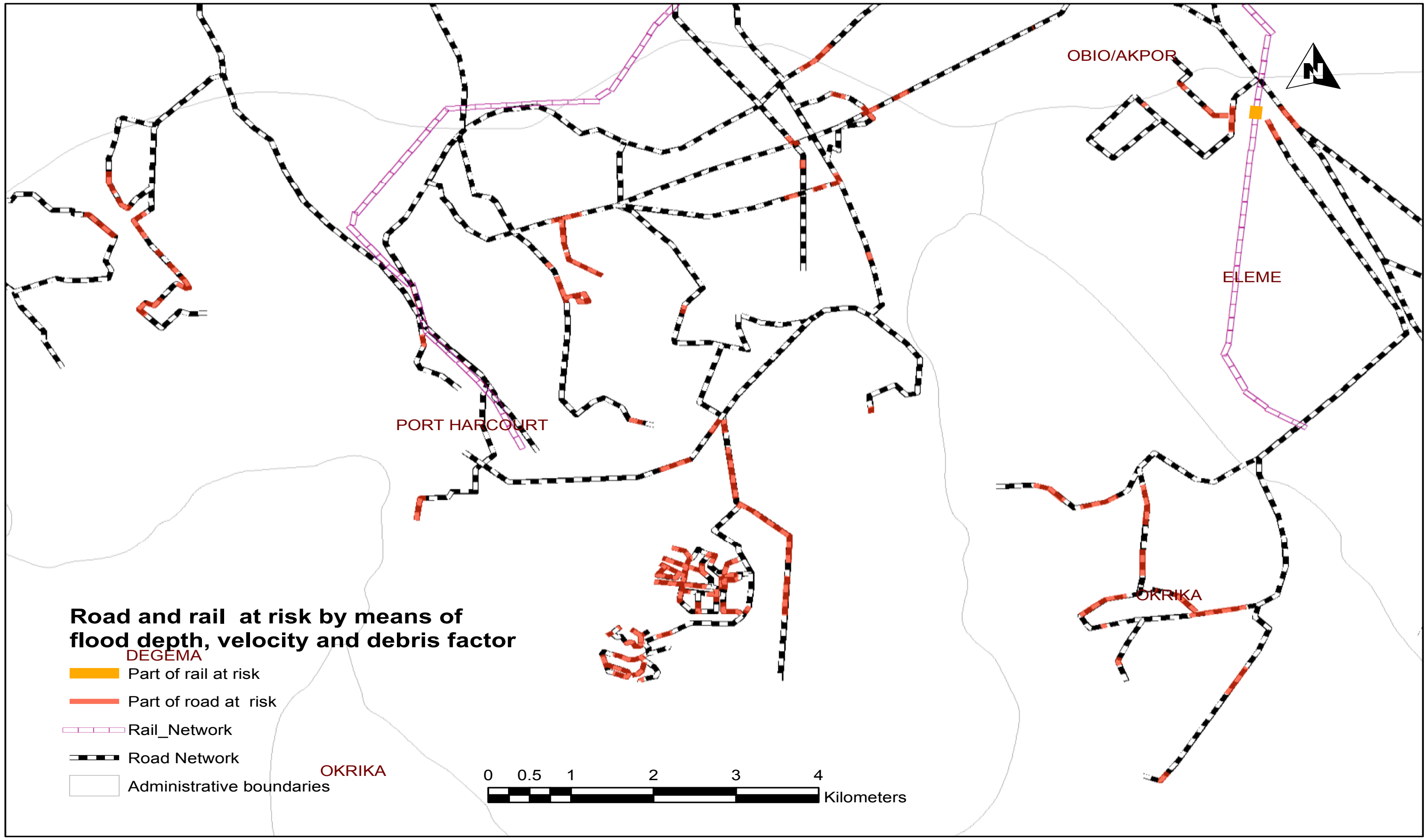

Figure 7.40 Map showing important roads at risk to flooding by means of exposured flood depth and flood velocity (Including debris factor).

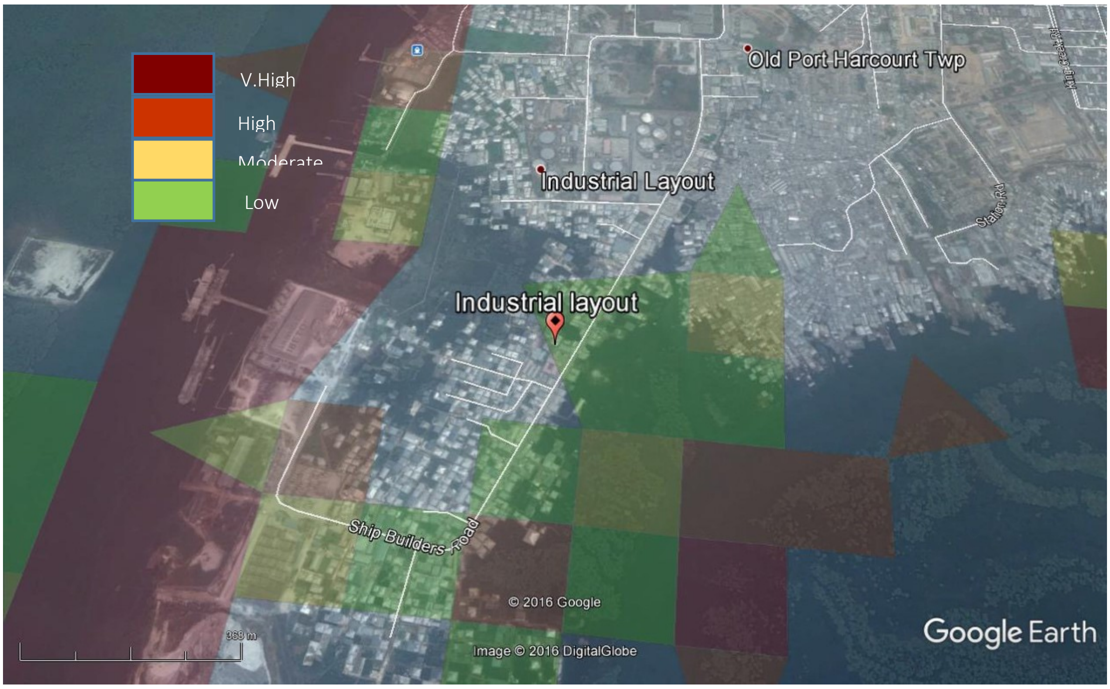

Figure 7.41 Buildings exposed to different hazard categories in the old industrial layout area.

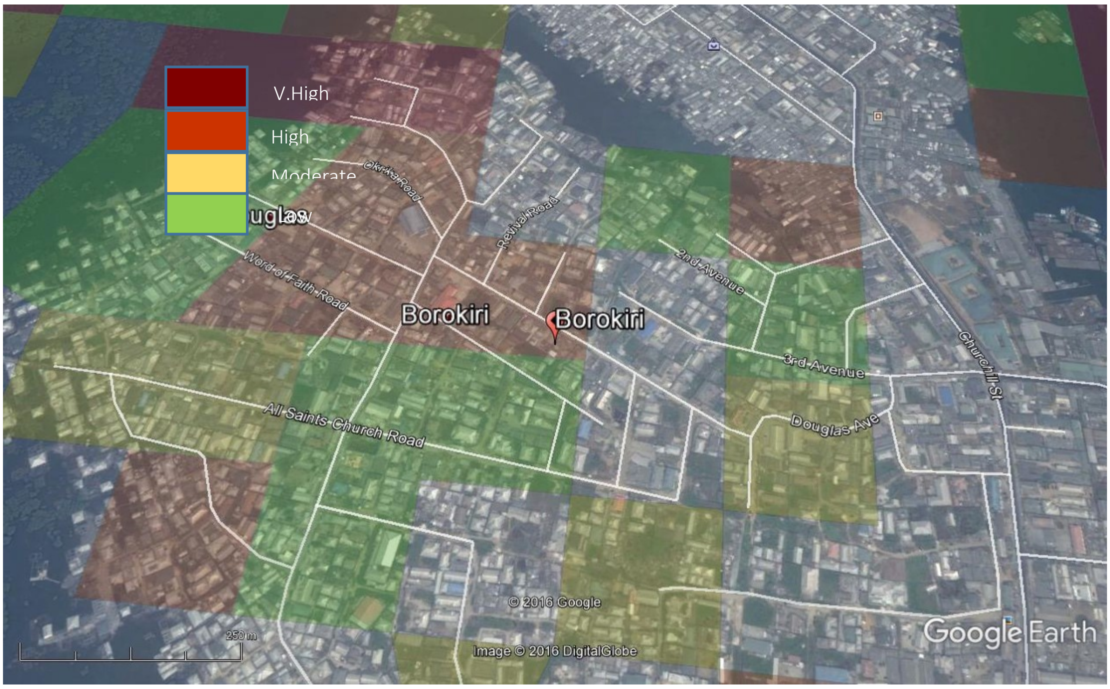

Figure 7.42 Buildings exposed to different hazard categories in the Borokiri area.

Figure 7.43 Buildings exposed to different hazard categories in the Abo Ama area.

Figure 7.44 Buildings exposed to different hazard categories in the Eastern by-pass area.

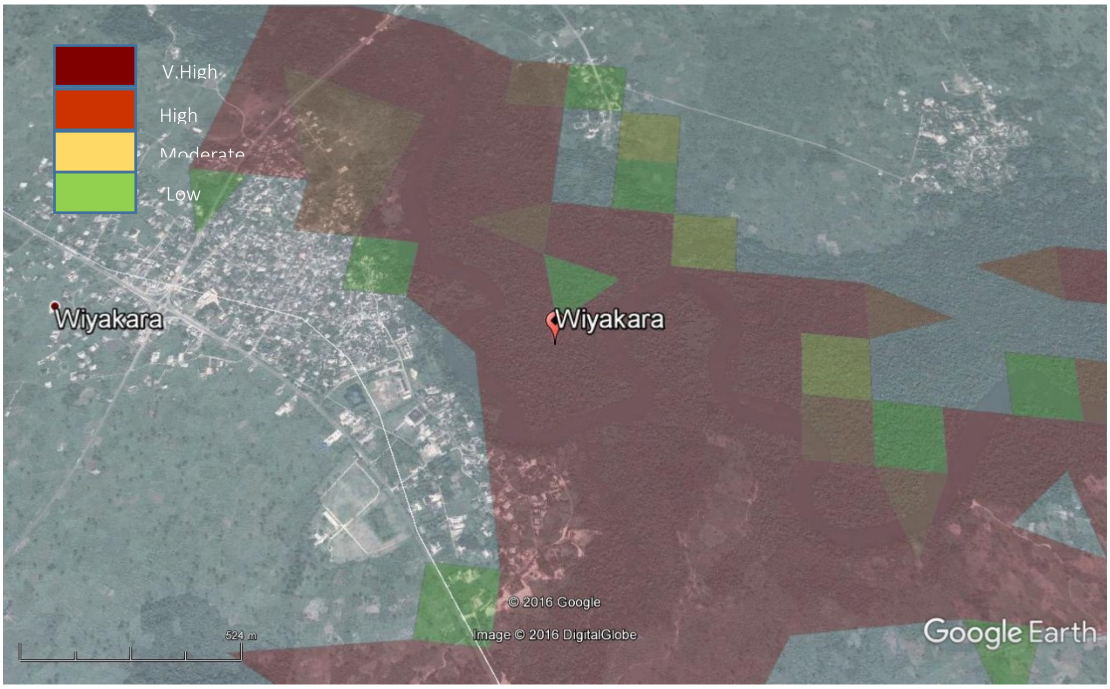

Figure 7.46 Buildings exposed to different hazard categories in the Wiyikara area.

Figure 7.45 Buildings exposed to different hazard categories in the Eagle Island area.

Figure 7.47 Buildings exposed to different hazard categories in the Onne Seaport area.

7.5 DISCUSSION

This study clearly demonstrates that hydraulic modelling and GIS approaches can be integrated and meaningfully used for assessing impacts, zoning flood hazards, rating flood hazards and identifying priority areas and elements at risk for planning and risk management purposes. The main goal of this chapter was to understand changes in flood hazard due to increased rainfall and urbanisation in Greater Port-Harcourt. Three important parameters including flood: depth, extent and velocity were used to analyse the impact of increased storm and urbanisation on floods in flood pathways. Based on the series of analysis, this study found that historic changes were significant and that significant changes are expected in future. However, the extent of change will largely depend on storm dynamic. Urbanisation would likely have little or no impact on flood in the selected river channels analysed (Tables 7.1, 7.2 and 7.4). The study argues that the effect of land use is very negligible compared to climate change factor and is consistent with the view of Hooijer *et al.* (2004). It implies that the changes depends more on the storm return period than land use. A significant increase in future flood depth and velocity in upstream areas mean that the majority of people living near river channel are prone to flood risk, e.g loss of life and to a lesser degree, damage to property.

7.5.1 Impact of urbanisation and storm on hydraullc condition.

Impact on flood depth.

Overall, based on analysis of RAS model output used to examine the degree of change, this study finds that the modelled area experienced a significant change in the past and is expected to undergo more signfiicant changes in the future. However, like runoff, the magnitude of change is largely dependent on the metrological condition. This means that despite the projected high rate of urbanisation due to the Masterplan, climate change will have a greater effect on water surface elevation in the watershed. For example, the analysis of depth dynamic in North Eleme reach (Figure 7.4) suggest that flood depth increased by about 0.8m between 1986 and 2003 events. Moreover, a substantial difference of about 0.5 and 0.7m is projected for this reach due to the A2 and A1B storms respectively. However, in future, the difference could be up to about 1.5m in the event of a 100yr storm flood. According to Duan *et al.* (2009), flood depths greater than 0.5 is a high hazard and may lead to loss of lives and damage to property. This implies that the effect of future storms on flood depth in the watershed could have could have devastating impacts on people and property. Note: bear in mind that there are some uncertainties with the results, which are due probable errors from the RAS model itself, assumptions made during spatial data preparation, as well as the quality of land-use, DEM and rainfall input data. Despite the uncertainties, the results were deemed reliable after validating the hydrologic and hydraulic model.

Considering changes in average depth for all modelled rivers, the analysis in Table 7.1 reveal that the difference in mean flood depth between 1986 (2.5yr) and 2003 (38yr) event is about 9m, while the difference in mean flood depth between 2003 (38yr) and 100yr storm event is about 16m. Generally, the analysis indicates that changes between the 1986 and 2003 events were statistically significant. Likewise, changes between 2003 event and UMP100yr scenario were statistically significant. This suggests that the impact of historical and future storms on flood depth across the watershed are significant. In contrast, the study revealed that changes in average flood depth due to urbanisation were insignificant in the past and could remain insignificant in the in future. In general, the data in this study strongly suggest that climate change is the main driver of flooding in Greater Port-Harcourt watershed. Secondly, the impact of urbanisation on flooding is projected to be negligible.

Comparatively, this study found that the effect of urbanisation on flood depth is insignificant contrary to findings for some other catchments in Birkhead *et al.* (2007); Qaiser *et al.* (2012); and Tripathi *et al.* (2014). These studies conclude that urbanisation had significant impacts on flood depth in channels. For example, Qaiser *et al.* (2012) found that flood elevation increased significantly in Kansas River, USA. In contrast, based on the analysis (Table 7.1), this study found that urbanisation did not have a significant effect on flood elevation. This means that the effects of urbanisation will be less significant with greater storms in future. One factor responsible for this phenomenon may be size of the watershed (Hollis, 1975). Another responsible factor may be the size of the storm because the effect of urbanisation is attenuated by extreme storms (Hooijer *et al.*, 2004).

The concluding point that climate change is the main driver is consistent with results in other studies (Hall *et al.*, 2005; Wagener and Franks, 2005; Adewale *et al.*, 2010; Tahmasbinejad *et al.*, 2012; Duvvuri and Narasimhan, 2013; Tripathi *et al.*, 2014). For example, Tahmasbinejad *et al.* (2012) conducted a regional study to generate water surface profiles for 2yr, 5yr, 10yr, 20yr, 50yr and 100yr events in Karun River Basin, Iszeh District, in Iran. The study result indicated that there was a difference of more than 1.5m of flood depth between a 2yr flooding and 100yr flooding. Similarly, in this study, a difference of about 1.7m in flood depth was observed between 2.5yr (1986) and 100yr events. Elsewhere in Nigeria, Adewale *et al.* (2010) routed flood in the Ogunpa river. The study found that changes in some parts of the Ogunpa River were up to 0.5m due to increased storm. Analysis of the longitudinal profile of different reaches in the study revealed that the historical and potential changes in flood depth vary from reach to reach, and in some reaches are more than 1.5m (Figure 7.4). In any case, the increase in flood depth corresponds with increase in storm size, which buttresses the fact that climate change is the main driver.

The most recent way of linking climate change to flood prediction has been through the use of Global Circulation Models (GCMs) (Wagener and Franks, 2005; Tofiq and Guven, 2014). Local downscaling techniques are used to adapt large-scale GCM outputs for local scale analysis. In this study, it important to restate that the 44yr and 57yr scenarios are based on IPCC SRES (Special Report on Emissions Scenarios - SRES) downscaled for Nigeria in the UNDP country profile report (McSweeney et al., 2010). Each scenario denotes different permutations of demographic, economic, social, environmental and technological developments that drive change in irreversible ways. In this case, the 44yr storm was derived from the A2 scenario which represents a heterogeneous world driven by regional economic development. Whereas 57yr storm is associated with the A1B scenario and depicts a world with rapid economic growth driven by new and balanced sources of energy. Since average depth of 57yr (A1B) flood is greater than 44yr (A2) floods, it implies that rapid growth in global economy despite the balance of energy sources is likely to cause greater impact on flood depth.

The exposure of people to flood hazard could be life threatening. According to Merz *et al.* (2007b), the most important indicators of flood hazard are water depth and velocity. Although flood depth and flood velocity are both important indicators of changes in the hazard condition, Wind *et al.* (1999) pointed that flood depth has the greatest influence on flood damage. This is because flood depth increases buoyancy, whereas flood velocity causes instability. Flood depth map show area with the greatest flood depth. Flood depths greater or equal to 1m can cause damage to urban areas depending on its intensity and velocity (Duan *et al.*, 2009; de MOEL and Aerts, 2011). Also, velocity greater than 0.5m/s is sufficient to cause damage.

In this study, flood depth maps (in Figure 7.17 to 7.27) reveal that many urban areas upstream are likely to be subject to floods greater than 1m due to a 100yr storm. For example, Figure 7.18 indicate flood depth flood could rise as high as 6.2m in the Abua/Egbema area and 3.2m in other areas. Around Emoha area, floods is projected to increase up to about 5.14m. This means flood may inundate up to first the floor of residential buildings in the area. Furthermore, flood depth is likely to rise as high as 4.9 m near Eleme/Onne seaport. This suggests that further increase in storm is likely to put facilities and installations in the seaports at greater risk of flooding. Floods as high as about 5.1m and 6.1m may also be experienced in the Bori, Khana and Kor area. Based on the flood depth assessment, this study projects that flood depth will likely be greater in the west (Egbema) and south-east (Kor area) of the study area. This implies that 100yr storm flood may put people in these areas at a greater risk of flooding. As stated earlier, keep in mind that there could be additional uncertainties with these results due to the quality of input data, assumptions and projections made for the input data, however, the results were deemed reasonable after validation and because uncertainties were not multiplied.

Effects on Flood Extent.

The analysis of flood extent based on lateral changes in the extent of maximum water surface elevation is another useful indicator for assessing impact and identifying potentially hazardous areas. Similar to flood depth, analysis in Table 7.2 indicate that substantial changes in flood depth occurred in the past and is expected to increase in the future. Again, the magnitude of change largely depended on the meteorological condition and not on urbanisation. Flood extent is directly influenced by other variables such as channel width, depth, velocity, discharge, channel slope, the roughness of channel materials (Horritt and Bates, 2002; Waheed and Agunwamba, 2010). A change in one variable causes a series of adjustments leading to changes in the other variables. In the past, flood extent increased by 15% between the 1986 (2.5yr) and 2003(38yr) event. In future, the analysis establishes that total inundated area is likely to increase further by 37% compared to the 1986 event and 20% relative to the 2003 event. That means that flood waters are expected to spread further by about 109km^2 and 66km^2 respectively. However, these results are presented with some uncertainties considering that there could be errors from digitisation, input data and assumptions made. Nevertheless, after validation of the hydraulic model the results were deemed reliable.

The substantial increase in flood extent driven by increased storm means that more areas of non-urban land cover types will be inundated and more people, properties, habitats are increasingly at of risk of flooding as shown in Figure 7.28-7.34. The Figures are 1: 10,000 to 1: 12,000 scale flood plain maps used for delineating flood zones based on extents of the 2.5, 38 and 100yr storm floods. Figure 7.34 show difference in flood extent measured around the Abonnema Wharf area. It can be seen that flood extent in the area increased from 445m to 506 and to 779m for the 2.5, 38 and 100yr events respectively. It clearly shows that flood from the 100yr storm is expected to inundate more urban areas. In this case, putting more people, buildings, industrial facilities at the seaport harbour at risk at risk. In short, changes in flood extent largely dependent on storm return period. Urbanisation is expected to have little or no impact on flooding. However, it is likely to increase exposure to flooding due to channel encroachment.

7.5.2 Flood zoning of the flood plains.

Apart from the extent delineations on flood maps, this study further demonstrates that outputs of the 1-D hydraulic model can meaningfully be applied in spatial planning for delineating flood zones. Based on the damage potential results and lessons learnt from previous floods in the area, this study supports the view that the construction of flood defences or use of structural measures alone cannot guarantee flood protection to a city (Faisal *et al.*, 1999; Islam and Ryan, 2016). Zoning is arguably one of most powerful regulatory instruments for flood risk management and spatial planning (Koks *et al.*, 2014; Islam and Ryan, 2016). Land-use zoning is a restrictive measure for prohibiting residential and industrial developments in flood prone areas. Its helps ensure that highly flood prone areas are spared from intensive capital investments and unplanned flood plain dwelling. It also important for steering new developments into low risk areas, preferably into areas with no inundation or relatively low inundation depths (Koks *et al.*, 2014). In this study, zones were used to categorise flood-prone land based on the probability of inundation. For academic purposes, the three flood zones delineated were based on 1 in 2.5, 1 in 38 and 1in 100yr storm flood extents with different probabilities.

From the analysis, it was found that about 20 km^2 of urban land could lie under the low risk zone 1. In this zone, low-frequency storms with an annual probability equal to or greater than 1% could occur. Whereas, as much as about 9 km^2 of urban area could lie under Zone 3. This is a high risk zone where storms with annual probability equal to or greater than 40% could occur. This means that buildings originally in zone 3 could be exposed to greater depths during the 100yr storms. From the images analysed in the study (Figure 7.29-7.34), the study finds that a high proportion of flood plain dwellers (bout 1104 buildings) are located in zone 3 (high-risk areas) than in Zone 2 (medium risk zone) especially around the old Port-Harcourt Township and Borokiri area (Figure 7.29). It is pertinent to state that number of building is the analysis is presented with some uncertainty because of the resolution of google map used and because the buildings were manually counted. However, it was good enough to show that many people in the area have been attracted to living around coastlines and flood plains in the past. It also implies that people in zone 3 are at greater risk of flooding which is a huge concern, because flood plain dwellers in zone 3 are likely to be exposed to floods with very high damage potential due to higher flood depth and proximity to the coastline. This is also concerning because a good number of people here live in poorly constructed houses made of timber and zinc materials (Akukwe and Ogbodo, 2015).

Based on these findings, this study recommends the use of zoning as a non-structural option in addition to the existing flood defence systems. Land use planning is used to optimise the use of land based on its geography, climatic and topographic characteristic. In this context, there is a Masterplan in place for existing and future development. Hence, I argue that flood zoning with appropriate regulation can help steer developments away from the high to low-risk zones. Flood zoning may also contribute to prevent urban sprawl and excessive erection of buildings in high-risk zones of future growth areas in the Masterplan.

For effective flood zoning, this study recommends the use of sequential test approach developed by the UK government for regulating floodplain developments found in the PPG25 (DCLG, 2009). This approach can help ensure that additional controls and procedures are followed to accommodate new development in flood plains. Zones 1, 2 and 3 can be designated advice, command and prohibited areas respectively. First, new developments should be located in in the advice area (Zone 1). However, if there are no available sites in Flood Zone 1, then a vulnerability study should be performed for land-uses, buildings and infrastructure. Developments should be allowed in the prohibited zone (zones 2) if suitable sites are unavailable zones 1 and 2. To accommodate new developments in Zone 3, vulnerability of land uses, building and infrastructure should be carried out with an exemption test. Regarding the exemption test, developers need to prove that the sustainability benefits of the development outweigh the flood risk.

7.5.3 Flood damage potential and Risk by means of exposure to flood hazard.

Apart from flood zoning, this study also demonstrates that information from the 1-D hydraulic model can be meaningfully used to identify areas at risk based on damage potential and exposure as supported in Van Alphen *et al.* (2007) and Merz *et al.* (2007a). The flood danger map revealed the damage potential of different areas based on hazard rating (Figures 7.41-7.47), while the exposure aspect helped identify important infrastructure and buildings vulnerable to flooding (Figures 3.37-7.40). Together, the integration of danger map and elements at risk (exposure) map help answer questions such as: what will be affected? What is the total length of road or rail at risk? Which important routes are at risk, how many buildings are under high damage potential in an area?

The analysis in Figure 7.36 displays the damage potential of modelled area. It can be seen that most overbank areas are significantly exposed to hazards with very high damage potential in the event of a 100yr storm. Figure 7.37 show location of important infrastructure and proposed land-uses at risk of flooding in the event of a 100yr storm. It was found that three seaports, the new military base, parts of the university, cement factory, and the Federal Ocean Terminal (FOT) in the over bank areas are likely to be affected. From estimation, a significant part (12 hectares) of the University of Science and Technology is at risk of flooding. Apart from the university assets are at risk. A nursery and primary school share the university space. Hence the lack of good emergency services in Port-Harcourt, coupled with the presence of schools with children between the ages of 5 and 11yrs make the place highly vulnerable to flood hazards. Moreover, from the map, the cement factory near the Port-Harcourt seaport could be affected by floods. Cement factories are considered potential source of pollution (Hindya *et al.*, 1990). There is evidence that increased levels of vanadium in water from cement factories inhibit soil-enzyme activities and could affect human health (Hindya *et al.*, 1990).

Appendix 7.6 reveal that about 248 buildings analysed in Figures 7.41-7.46 are subject to very high flood hazard characterised by deep and fast flowing water. Regarding roads and rail network in the city, Figure 7.37 show a map of important and proposed roads in the studied area. From that map, it was found that about 37.1 km of roads could be affected by the 100yr storm flood. The study also found that approximately 27% (8.1km) of the affected area is projected to be exposed to floods with extreme floods characterised by very high damage potential. This means about 8.1km (27%) of the affected road network network could be exposed to floods with deep and fast flowing water which could be dangerous for all road users. Again, these results are presented with some uncertainties from possible errors due to the resolution of the exposures map, quality of input data, digitisation and assumptions made, however, after validation the results were considered reliable. The important message is that extreme floods in this area could lead to major disruptions and cause difficulties including damage to roads, damage to vehicles, closure of evacuation and emergency routes. Total submersion of roads could also cause financial losses and temporary hardships due to obstruction of the main haulage routes such as the East-west road.

Similarly, the 2012 flood events submerged roads, drowned cars and lead to deaths (GFDRR, 2013). The map in Figure 7.40 also indicates that 61m of the rail network could potentially be affected by flooding. Although this is comparatively a smaller part of the rail network, it was found that all parts of the affected area would lie under extreme flood with very high damage potential. This impact is potentially significant because there is just one rail route in and out of Rivers State. Haulage of goods in and out of the state could be disrupted as a result. Also, the study found that roads in the southern part of the study area are more likely to be affected than those in the north Figure 7.38. In addition, debris are likely to affect the rail and road network during flooding events. Until debris are removed, they may act as a barrier on roadways and prevent travel. Therefore, a combination of structural and non-structural measures should be put in place to mitigate flood risk and exposure of roads to flooding to avoid major disruptions and hardships.

In the context of flood risk management, structural measures are interventions that involve physical construction to avoid conceivable impacts of hazards or the application of engineering methods to achieve hazard resistance and resilience in structures or systems, e.g. sea walls, sediment-trapping structures, detention ponds. On the other hand, non-structural measures are used to lessen the likelihood or consequence of flood risk through modifications in human action, human behaviour, or natural processes e.g. setback regulations, zoning, eminent domain, and building codes etc. (Islam, 2016).

7.5.4 Other Implications for the GPH Watershed.

Socio-economic implication.

This study finds that flood depths greater than 1m and flood velocities greater than 0.5 m/s as well as flood extent greater than 1 km^2 are could accompany 100yr storm floods in future. This could incur socio-economic costs. Compared to most developed regions of the world, it is well known that people in coastal areas in this region are more vulnerable to the impacts of climate change and natural hazards due to their proximity to the coastal environment, topography, low adaptive capacity, dependence on resources sensitive to climate changes and above-average climate change (Christensen *et al.*, 2007; Ajaero and Mozie, 2012; Jha *et al.*, 2012; Müller *et al.*, 2014; Tami and Moses, 2015). Many people in the area dwell in floodplains (Figure 7.41-7.47) especially in the southern part of Port-Harcourt and poor people are lured to coast line and are increasingly encroaching into flood channels due to their inability to secure planned housing inland (Obinna *et al.*, 2010). These group of people are more at risk to flooding in the event of low and high probability storm floods. The impact of increased flood hazard may incur direct and tangible costs such as damage to crops, damage to private buildings and properties; damages to vital infrastructure including railroads as discussed earlier. Flood disaster may also interrupt businesses, rescue and evacuations, clearing and clean-ups, as well as damage to harvest and livestock.

Loss of life

One major implication of increased flood levels is the potential for the loss of lives during flood events. People in upstream areas, especially is areas described in the previous paragraph are likely to face the risk of death in the event of very low probability flooding. Flood intensity depends on flood depth and velocity (Schanze, 2006; Moel *et al.*, 2009). From the analysis of flood depth, parts of the upstream reaches such as the Trans-Amadi, Elelenwo, Eleme, Okrika, Eagle Island, Bori and southern Port-Harcourt are likely to experience floods with high damage potential due to floods greater than 1.0m and velocity over than 0.5m/s. As flood intensity continue to rise, a neutral equilibrium is reached, after which people, properties depending on size may begin to float. Research show that depths more than 1.0-1.37m is sufficient to lift infants to adults (Van Alphen *et al.*, 2007; Duan *et al.*, 2009; Moel *et al.*, 2009). If accompanied by higher overbank velocities greater than 0.5m/s, it may cause substantial loss of lives. Wagener and Franks (2005) have argued that extent of flood damage does not only depend on flood characteristics but also on vulnerability and adaptive capacity. Other studies have argued that the risk of death may be increased by inadequate flood warnings systems, lack of structural and non-structural flood management systems. Also, losses can be direct and intangible (Merz *et al.*, 2010). Apart from death, this study adds that flood disasters in GPH to a lesser degree may cause injuries and psychological distress.

Environmental impact.

On the environment, high-intensity floods may affect the catchment ecological integrity. The Niger Delta River Basin is a receiving environment located downstream and the southernmost part of the Niger River systems (as described in chapter 3). Due to its unique hydrographic, hydrologic and geologic setting, its ecological system considered very rich and biologically productive may experience degradation due to pollution from flooded industries. There are many possible sources of pollution related to flood effects (Smith, 2013; Hewitt, 2014). Apart from industries, chemical and oil spillage from oil industries and petrol stations could result (Snowden and Ekweozor, 1987; Osuji *et al.*, 2004).

In this study, hazardous chemicals from factories and installations at the seaports around Port-Harcourt and Onne are potential sources. Leachates from planned landfill may unlikely affect the waters but leachate from existing landfills and dumps may also be a source of concern. Other issues may include effluence from septic tanks as wells as fertilisers from agricultural lands in the Bori and Emohua areas. Other chemicals such as heavy metals (lead, cadmium, etc.) might also be transported. These are easily absorbed by soils and could be carried as sediment in the flood-chain. In the event of the 100yr storm flood, these substances may be transported through different ecological zones. Since greater storms affect flood extent, it means future climate change may the reach of a pollutant and result in substantial degradation in water quality.

In Port-Harcourt, not much has been done to assess post-flooding contamination in the area, but incident in Labe (Elbe) River in Prague help suggest that spillage from industries can be carried into rivers. In the case of Labe River, about 81 tonnes of chlorine gas and liquid from a chemical plant 20km north of Prague was reported to have leaked into the River (Gautam and Van Der Hoek, 2003). Laboratory analysis concluded that abnormal levels of dioxins (three time above safety levels) were observed in a Libis a village 0.5km downstream of Spolana. Although, the full scale of the impact would be realised in several years to come, the incident posed a great threat to elements at risk especially to aquatic life in the area which can also adversely affect humans through food chain (Gautam and Van Der Hoek, 2003). Similarly, flora and fauna especially those found along floodplains in the study area face a greater risk of sediment and water pollution due to the dense river network, low adaptive capacity and the presence of industries in the flood plains of the study area.

7.5.5 Applicability of Research

This study clearly demonstrates that hydraulic modelling, GIS approaches as well as data from PUB methods can be integrated and meaningfully used for assessing impacts, zoning, rating hazards and identifying priority areas and elements at risk for planning and risk management purposes in the GPH area. Importantly, the methods have been meaningfully integrated and used to provide important messages about direct risk to life in such an economically deprived and data-sparse region. Perhaps it means that the approaches and methods employed in this study can also be applicable or is likely to work well for flood risk management research in other data-sparse and economically deprived coastal cities in Nigeria and other developing countries that are faced with similar problems. For example, findings of this study reveal that peak discharge, flood depth and flood extent increased considerably in the past and is likely to increase in the future; moreover, the potential increase could mainly be due to increased storm and not urbanisation. The approaches used could be applicable in studies of cities in other large tropical watersheds within the Niger Delta regions since they have similar climatic and physiographic conditions. Such cities include Warri, Calabar, Yenegoa and Uyo in Nigeria. Again, due to high intensity of rainfall, rapid development and size of the watersheds, the findings of this study could also be applicable to cities in other large tropical watersheds around West Africa and Asia such as Conakry in Guinea, Grand-Lahou in Ivory Coast, Douala in Cameroon, Hanoi in Vietnam, Dhaka in Bangladesh etc. In nut shell, the integration of PUB hydrologic approaches, hydraulic modelling, zoning, the assessment of direct risk to life and identification of priority areas used for this flood risk management research could be applied in similar socio-economic regions of the world.

7.6 CONCLUSION

Based on the analysis, this study concludes, firstly, that flood hazard increased significantly in the past and is likely to amplify in future; however, the projected increase will largely be due to increased storm or climate change and not urbanisation. Changes in flood depth is the main measure of flood hazard in river channels. This study has demonstrated that urban areas and agricultural lands around Abua and Egbema area in the north-west, as well as Kor area in the south-eastern part of the city are likely to experience higher water surface elevation up to 6.7 and 6.5m respectively. Meanwhile, flood velocity may not increase significantly in future, which could be due to the slope of downstream channels.

Importantly, urbanisation may likely have little or no impact on the hydraulic condition of river channels, on the other hand, this study concludes that rapid urbanisation would likely increase flood risk due to greater exposure of people, buildings and critical infrastructure resulting from planned and unplanned developments in coastal areas. This is illustrated in Figure 7.37 where the proposed Air Force base and residential area near Onne seaport are projected to be affected by the extreme (100yr storm) flood. Although the Masterplan has been proposed and approved, this study suggest the need for improved flood risk management in these areas of the Masterplan.

Again, the study found that as much as about 20km^2 of urban land lie under low risk zone (Zone 1), while about 50% (9 km^2) of this area fall under prohibited high priority zone (Zone 3). A number of districts selected for analysis indicated that there are more floodplain dwellers in the high-risk zone 1 area than medium risk zone 2 areas. Zoning is more effective in bare areas, and may be less effective where there are existing structures. Therefore to reduce flood risk where there are existing structures, this study suggest the need for the integration of structural and non-structural measures. Relocation of flood channel dwellers to safer areas could also help reduce flood risk. On the other hand, the strengthening of primary flood defences can be done. In this case, the 100yr storm floods can be used as design storm for constructing flood defence structures around the Onne seaport area.

This study found there are four flood risk management hots spots, in terms of important infrastructure at risk of flooding. These include the University of Science and Technology, two seaports in Port-Harcourt and the Onne seaport (Figure 7.37). Importantly the study concludes that around 37km and 61m of road and rail could be affected. About 8.1 km of the potentially affected roads could be submerged under extreme floods with very high damage potential characterised by deep and fast flowing water. It is important to restate that results in this chapter are presented with some uncertainties due to possible errors from map resolution, input data quality, digitisation and assumptions made, however, the results were deemed reliable after validating results from the hydrologic and hydraulic models. The important message is that the size of the flood hazard could increase and that extreme floods in this area could lead to major disruptions and may cause difficulties including damage to roads, damage to vehicles, closure of evacuation and emergency routes.

The implications for this watershed include, socio-economic costs, environmental costs, loss of lives, injury and stress. Therefore, the study recommends the greater use of preventive or non-structural measures such as zoning for steering away developments from floodplains. In particular, the sequential test approach can be applied as an additional control measure. Importantly, this study demonstrates that one-dimensional hydraulic modelling is useful for simulating the impact of catchment developments on the hydraulic conditions of rivers. It also shows that the output of hydraulic models can be helpful for informing flood risk management and land use planning in the studied area. Finally, this study concludes that increased urbanisation like in the past may not affect flooding instead, climate change could remain the main driver of flooding in the region. Nonetheless, increased urbanisation may lead to greater exposure of flood plain dwellers to flooding due to channel encroachment.

8 GENERAL DISCUSSION & CONCLUSIONS

8.1 REVIEW OF AIM AND OBJECTIVES.

The main objective of this research was to understand the effects of land-use and climate changes on flooding in the Greater Port-Harcourt watershed. The main research questions addressed were as follows:

- What are the historical and future changes in the LULC of Greater Port-Harcourt Watershed? (**Addressed in Chapter 5**).
- What are the effects of land-use changes and climate change on flooding in the GPH watershed? (**Addressed in Chapter 6 and 7).**
- To what extent could afforestation reduce flooding in the GPH watershed? (**Addressed in Chapter 6**).
- How can the Greater Port-Harcourt Development Authority improve future planning using new insights into flood risk? (**Addressed in Chapter 8, section 8.2.4**).

This Chapter synthesises and presents the main findings, implications and lessons learnt. The findings were then used to make recommendations. The synthesis of the main findings was presented in section 8.2 by addressing each of the research questions listed above. Section 8.3 presents the academic contributions of this study. Section 8.4 presents the limitation of study. Conclusions based on evidence in this study was presented in section 8.5. Lastly, further research was elaborated in sections 8.6.

8.2 SYNTHESIS OF FINDINGS AND LESSONS LEARNT

8.2.1 What is the extent and nature of LULC changes in the Greater Port-Harcourt Watershed?

This study found that the watershed experienced significant changes in the spatial extent of urban land-use between 1986 and 2003 (Table 5.1). In the future, significant changes are also likely to occur due to the implementation of the GPH Masterplan by 2060 (Table 5.17). Specifically, urban area may nearly double its 2003 extent by 2060, i.e. from about 550 km^2 to about 998 $km^{2,}$ which is approximately an 80% growth. Similar to this finding, a recent study by Mmom and Fred-Nwagwu (2013) have also shown that urban area increased significantly between 1986 and 2007 by 86%. On the contrary, Enaruvbe and Ige-Olumide (2014) reported that only 10% change occurred. The difference in the degree of change reported could be due to the difference in the extent of study area. While the study area covered by the previous studies ranged between 400 and 570km^2, the spatial extent of this study was about 4821km^2. To date, there is no knowledge of future land-use change found in studies for the study area. Hence, this study extends knowledge of the GPH watershed by providing new insights into future land-use dynamics by showing that urban area could increase significantly in 2060 by about 600% from 1986 or 80% from 2003 (Figure 5.12), which theoretically could have flood risk implications. Bear in mind that these results are presented with some uncertainties due to possible errors from digitisation, input data quality and assumptions made. Nevertheless, LULC change results were deemed reliable based on the reliability of the classification method applied, similarity in the trend of changes when compared to prior studies and the author's knowledge of the landscape. Based on the data in this study (Table 5.13), I found that urbanisation and loss of agricultural land were the dominant forces of land use change in the GPH watershed. However, urbanisation have been the key driving force of land use change in the past and is likely to continue in the future. In fact, the watershed experienced a drastic rise in urban area along with a decline in agricultural land and forestland, with a slight decrease in mangrove and water classes.

Regarding the nature of change, data in this study revealed that three quarters (about 75%) of the watershed persisted to change, while as much as 25% of the watershed transition from one land use category to another between 1986 and 2003 (Table 5.13). This study found that, unlike other LULC categories, transition of urban land was the most dynamic in terms of gross gain and net change, which according to Lu *et al.*, (2004) and Manandhar *et al.*, (2010) are the important measures of expansion. Urban area exhibited the grossest gain (about 9% of the watershed) and the grossest loss leading to a high net change of around 8.6%. In fact, the most prominent transition was historically the conversation of agricultural land (about 422km^2) to urban land (Table 5.5) with about 93.3% of all conversions to urban land resulting from agricultural land. The study also revealed that the prominent non-urban shifts were from forest to agricultural land (approximately 321.0km^2) and from agricultural land to forest (about 229.5km^2) between 1986 and 2003 (Table 5.5) which one might not expect. However, it explains why swap changes occurred (as expounded in the next paragraph). Based on the above, I establish that the most important shift in the entire watershed was from agriculture to urban land. Moreover, urbanisation occurred chiefly at the expense of agricultural land. This finding relates to the whole watershed and corroborates with previous findings which covered a smaller part of the landscape.

Importantly, this study extends research in studied the watershed by providing new insights on the process of change that occurred historically between 1986 and 2003. Based on the data in Tables 5.13 to 5.15, I found that the urban transition was dominated by net changes. In contrast, other prominent non-urban transitions were dominated by swap changes. This implies that the transition from agricultural land to urban land experienced an actual change in extent than a change in location. In hydrology, one would expect that changes in the extent of impermeable surfaces due to urbanisation would compound flood risk more than changes in location. In contrast, agricultural land and forestland transitions mainly underwent a process of swap change than net change, which means a considerable amount of these land-use categories experienced relocation. The relocation of forest land could still have some flood implications for some small subbasins because of changes in the surface roughness in the local subbasins. The phenomena observed in the GPH area was comparable to occurrences in the Mara River Basin in East Africa, for which Mwangi *et al.* (2016) found that swap changes accounted for more than 50% of the overall LULC changes. In this study, swap changes accounted for over 60% of the total changes in the GPH watershed. This suggests that the GPH watershed is very dynamic. I therefore support the argument that reporting only net changes can underestimate the total land-use changes in landscapes (Pontius *et al.* 2004).

In addition, this study has furthered understanding on the watershed in terms of LULC tendencies to change. I found that urban land exhibited the highest gain-to-persistence ratio of 4.6, which was well greater than 1 (Table 5.16). This means that urban land exhibited the strongest tendency to expand. In contrast, agricultural land exhibited a low tendency to expand. Meanwhile that of forest was two-tailed, showing a tendency to expand and contract. Based on the data of extent of change, trend of change, process of change and tendency of change presented, this study emphasises that urbanisation have been the most dominant force of land use change in the watershed and seems likely to accelerate in the future. Keep in mind that the results (and percentages) in chapter 5 are presented with some uncertainties due to possible errors from different sources such as data quality, digitisation and assumptions made in the study. While LULC results are not perfect, the results in this study were deemed acceptable because of the reliability of the methods applied, the author's knowledge of the landscape and consistency with the trend of change when compared with results in prior studies. The important messages results were not significantly affected by the uncertainties and that: (1)

urban expansion was rapid, (2) the expansion could rapidly increase by 2060 due to the GPH development, (3) the rapid urban expansion occurred mainly at the expense of agricultural land.

8.2.2 What are the effects of land-use and climate changes on runoff in the GPH watershed?

Historically, this study found that changes in annual maximum peak flow increased significantly (by about 68%) between the 1986 and 2003 event. Although the substantial change in annual maximum peak flow corresponded with increased urbanisation, impervious surface and storm size between 1986 and 2003 (Table 6.6 and Figure 6.1), further analysis revealed that urbanisation had little or no impact on extreme peak flow at the watershed scale. That is, the impact of urbanisation on runoff was insignificant. This differs from findings for other basins e.g. the Lai Nullah Basin in Islamabad, Pakistan in Ali et al. (2011). Ali *et al.,* (2001) noted that change was significant due to urbanisation. On the other hand, it is consistent with findings in the work of Hollis (1975) which showed that urbanisation did not have a significant effect on runoff. Based on the data (Table 6.7), I argue that drastic changes in maximum peak flow in the GPH basin is largely attributed to increased storm size and not urbanisation. This is consistent with views in some studies, e.g. Parker (2000); Singh et al. (2006), who noted that rainfall is the main driving force of change. In relation to the impact of urbanisation on the GPH watershed, results in this work differs from findings a local study by Thecla (2014) who interviewed respondents and found that urbanisation is a major factor influencing flooding. However, I argue that the significant increase in extreme peak flow within the historical period can be attributed to increased storm size rather urbanisation because there were no obvious changes in annual maximum peak flow due to increased urban area for both historical and future periods (Table 6.7). Secondly, the local inquiry method applied in that study may likely not account for basins outside the immediate vicinity where respondents lived. In contrast, this study used numerical modelling method that accounted for spatial and watershed scale changes beyond residential areas where people live.

Despite the dominant role of rainfall on flooding in the watershed, I also found that urbanisation had considerable impact on peak flows in a number of local subbasins (Appendix 6.9). Affected subbasins include BUGW100, DEGW250, and DEGW240, with the greatest effect in DEGW160. This means there was little or no change at the watershed scale, but at a subbasin scale, the changes in some subbasins were substantial. One lesson learnt was that the effect of urbanisation on floods in the studied catchment area depend on the scale considered. It is pertinent to point out that there are some uncertainties in these results due to possible errors from the model itself, the quality of spatial and topographic input data used as stated in subsection 4.4.1. However, the results were deemed reliable after validation with independent data in published work, which showed a reasonable performance. Moreover, overestimation and underestimation would cancel themselves out and would result in the uncertainty not having a significant effect on the result or the main message. The main message is that changes in extreme flow increased progressively and became significant by 2003. Another lesson learnt is that the comibination of multi-date and multi-source data can generate uncertainty that could affect research findings and need to be carefully considered when embarking on flood risk research in data sparce regions.

In future one might expect a significant impact on runoff due to the implementation of the GPH Masterplan as seen elsewhere. However, the data in this study revealed that urbanisation is likely to have little or no effect on runoff at the watershed scale. Beyond the evaluation of historical changes, this study extends research in this watershed by providing new insights into potential changes in peak flow due to future urbanisation. Comparable to the historical trend, I found that increased storm is likely to have significant effect (of about 80 % change from 2003) on annual maximum peak flow at the watershed scale, in contrast a significant effect of urbanisation on annual maximum peak flow resulted is not expected (Table 5.13), bearing in mind the results are presented with some uncertainties. This finding varies from that of Ali et al. (2011) who found that future urban land-use as envisioned in the Masterplan was expected to raise peak discharge between 45.4 and 83.3% in the Lai Nullah Basin in Islamabad, Pakistan. On the other hand, my findings corroborates with findings in Hollis (1977, 1979) and Shuster et al. (2005). Hollis (1979) found that there was no difference in maximum monthly discharge with large floods ⩾ 20yr. Shuster et al. (2005) argued that higher peak flow and associated low-frequency precipitation events were less sensitive to urbanisation which was the case for GPH watershed. This phenomenon might be explained by the theory that higher storms saturate catchments easily and reconditions the watershed's surface to become like impervious surfaces, such that further increase in urban cover no longer affect the peak flow (Parker, 2000; Du et al., 2012). Nevertheless, I also found that urbanisation is likely to have considerable effect on about twelve (12) subbasins including AOW40, AOW50, BUGW100, IMOW70 IMOW80, IMOW100 BUGW130. Therefore, I project that the impact of the Masterplan will more likely to be pronounced in a number of small subbasins.

8.2.3 What are the relative effects of the location alternative to Phase-1 project on flooding in the GPH watershed?

On the effects of locational alternatives, I found that the Omoku-Ogba alternative had the lowest impact on runoff (Figure 6.9). The Bori location alternative generated a greater change in peak flow than the Omoku-Ogba and current project alternative. This implies that developments with the same spatial extent at different locations (basins) cause different effects in the subbasins analysed. This trend is the same for subbasin scale changes and is consistent with the view of Glasson *et al*., (2013) who noted that different alternatives are likely to generate different effects. I also found that the placement of impermeable surface within the three subbasins (whether upstream or downstream) did not have profound influence on runoff. The Bori alternative in the smallest basin generated the greatest change, which suggests that basin size could be a more important factor than location of a development in those subbasins.

8.2.4 To what extent could afforestation reduce flooding in the GPH watershed?

In terms of the effect of forest, this study revealed that increased vegetal cover is likely to cause little or no changes in maximum peak flow when considered at the watershed scale (Table 6.9). Further analysis revealed that increase in the area of forest cover is likely to produce different effects across all sub-basins. This means that afforestation can play little or no role in reducing extreme flows in the entire watershed. I also found that the effect of vegetal cover on peak flow declined with increased storm return period (Appendix 6.11) which is supported in theory. These findings suggest that the use of afforestation in mitigating extreme flows in large storm conditions may not be effective in the GPH watershed.

The effect of forest on large catchment is relatively more unclear in studies than its effects on small catchments, as no consensus has been reached. The findings of this study corroborates with findings in Wilk et al. (2001) and Bart & Hope (2010) who found no obvious changes in peak flow due to changes in vegetal cover. Bart and Hope (2010) concluded that the changes in streamflow were rather dependent on post-fire wetness conditions than deforestation. On the other hand, the findings in this study vary from results for other large catchments. Jones and Grant (1996) found that forest harvesting amplified peak discharge by as much as 50% in small basins and 100% in large basins over the past 50 years in the Western Cascades, Oregon. Likewise, Mwangi et al. (2016) showed that flow in the Nyangores River in Kenya increased significantly over the last 50 years and that changes in vegetal cover contributed to 97.5% of the change in streamflow (2.5%) and this was due to climate variability. For the GPH watershed, I found that the reverse is the case; peak flow is insensitive to afforestation when considered at the watershed scale (Figure 6.7). Hence, the study concludes that rainfall is the main driver of hydrologic change and the effect of forest on runoff is very unpredictable in local small subbasins (Figure 6.7b), again bearing in mind that result of this subsection are associated with some uncertainty from a number of sources.

8.2.5 What are the effects of land-use and climate change on flood hazard in the GPH watershed?

Based on the comparison of result outputs, Table 7.1 reveals that significant changes in flood depth occurred in the past and that significant changes are projected to occur in the future, however little or no change is expected to occur due to increased urbanisation. Changes in flood depth will likely be caused by increased storm. Flood depth is known to have the greatest effect on people due to buoyancy effect, and is projected to rise up to about 1.5m in the North Eleme reach. In the event of a 100yr storm flood, the study found that flood plain in the northwest (Abua and Egbema areas) and southeast (Bori and Kor areas) are expected to be exposed to the highest flood depth of up to 6.2, 6.7, 5.1, and 6.5m respectively (Figure 7.19-7.27). Recall that these results are presented with some uncertainties considering that there could be errors resulting from digitisation, map resolution, input data quality and assumptions made. Nevertheless, the results were deemed reliable after validation of the hydrologic and hydraulic models.

This study found that changes in channel velocity due to increased storm are expected to be insignificant which could be due to the slope of the watershed. Channel velocity is often greater with steeper channel slopes (Chow, 1959). Higher flood velocity is expected to occur upstream in the Northwestern Obio/Akpor area (Figure 7.35). Regarding flood extent, the model data revealed that considerable changes (up to about 15%) occurred in the past and a greater change (up to about 20%) is expected to occur in the future, however, the magnitude of change largely depend on rainfall than urbanisation (Table 7.2).

Land-use zoning is a restrictive measure for prohibiting residential and industrial developments in flood prone areas. It is useful for steering new developments into low risk areas, preferably in areas with no inundation or relatively low inundation depths (Koks et al., 2014). In this study flood zones based on three storm flood probabilities were defined to identify priority areas. The study found that about 9km^2 of the affected urban area fall under the prohibited zone (Zone 3) (Table 7.5b). For the areas analysed, about 2618 buildings could lie in zones 1, 2 and 3, and as much as 45% (1195) of the buildings potentially lie in zone 1 and these zones could be flooded by 2.5yr storm flood (Figure 7.5). This implies that there are more flood plain dwellers in a zone 1 area with higher risk than those in zone 2 with medium risk, suggesting the need for improved flood risk management especially in zone 1 areas. Keep in mind that some uncertainty are associated with counting of the buildings, nevertheless the important point is that increased storm put flood plain dwellers at greater risk.

This study also found that important infrastructure at risk of flooding include: the University of Science and Technology, the cement factory, 2 seaports in Portharcourt and 1 seaport at Onne (Figure 7.37). In addition, this study revealed that approximately 37km of the road network and 61m of the rail network are potentially at risk of flooding (Figure 7.38-7.40). Importantly, around 8.1 km of the potentially affected roads could experience extreme floods with very high damage potential characterised by a deep and fast flowing water. The implications for the watershed could include socio-economic costs, environmental costs, loss of lives as well as injuries and stress. This study also reveal that priority areas in the proposed Masterplan could include the Air force base and residential area (near Onne seaport), see Figure 3.37. The above areas could be affected by extreme (100yr storm) floods.

8.2.6 Recommendations: (How can the Greater Port-Harcourt Development Authority improve future planning using new insights into flood risk?)

The Greater Port-Harcourt Development Authority can improve future planning using new insights into flood risk in this study. First, this study identifies important planning and flood risk management issues in the watershed that needs to be addressed. They include:

1. Impact of urbanisation on runoff in local subbasins
2. Impact of climate change on runoff, flood depth and flood extent
3. High exposure of existing buildings to potentially damaging floods
4. Exposure of important infrastructure
5. Exposure of roads and rail network to floods with very high damage potential
6. Exposure of proposed areas in the Masterplan

7. Data quality issues
8. High cloud cover issues

Generally, this study recommends the integration of structural and non-structural measures for minimising the adverse impacts of climate change and urbanisation on runoff in the subbasins. For minimising runoff, it also recommends the use of land development controls aimed at minimising development of impervious surfaces and unnecessary hardscapes in the subbasins. This can be achieved by using land zoning and other related ordinances to restrict unnecessary developments. Again, the percentage of allowable impervious surface within developed parcels in high-risk zones should be regulated. The GPHDA should increase the number of detention ponds. Detention ponds should not be limited to the new city alone. More detention ponds should be constructed near existing high densities to prevent local flash flooding. Rainfall is a major source of inland flooding in the GPH watershed, hence significant improvements should be made in developing and improving detection and forecasting systems. The land controls, flood prevention and subbasin management methods should be based on the hydrodynamics of local subbasins.

To minimise flood risk of buildings and important infrastructure to flood hazard, a number of structural and non-structural measures can be integrated. For existing flood plain dwellers in the old city, property protection measures should be used such as retrofitting and relocation of buildings in high-risk areas. Presently, a number of unplanned houses built with roof sheets are found in the south of Portharcourt. Such buildings in high risk zones can be demolished while residents are relocated to safer areas to minimise future losses. Structural retrofitting methods such as dry flood proofing is also recommended for reinforcing and modifying the buildings in planned areas. This could help in preventing or reducing potential damage from hazards. Moreover, shoreline protection structures such as seawalls, bulkheads, and revetments designed for 100yr storms should be erected near the shoreline especially in the south of the old city. Although some structures exist in the old township areas, newly developed areas in the south such as the Borokiri sand filled area require shoreline protection to prevent the impacts of flood hazards.

For newly developed and bare areas, non-structural or preventive measures such as zoning should be implemented to restrict or steer away developments from flood plains. According to Islam and Ryan (2016) zoning is more useful for bare areas. For effective flood zoning, this study recommends the adoption of the sequential test approach developed in the PPG25 by the

UK government for regulating flood plain developments (DCLG, 2009). This approach will help ensure additional checks are put in place to accommodate new developments in high-risk areas such as zone 1 (See subsection 7.5.2 in chapter 7 for more details). This approach can also help prevent urban sprawl in undeveloped flood plains. Lastly, roads and rails should be protected by elevating them above the base flood elevation to avoid disruption and maintain dry access.

For flood risk management research, this study recommends that future flood risk management should not solely be based on the effects of climatic and non-climatic factors on watershed hydrology and river hydraulic condition, but studies should also consider priority land-uses, infrastructure and ecosystems likely to be affected by future flooding. This study demonstrates that the assessment of the impact on physical flood hazard alone without considering elements at risk in a watershed may be misleading in understanding the effects of urbanisation in the watershed. For other regions and countries, researchers and practitioners should also consider the dynamic in the exposure of important elements at risk within the floodplains under study to better understand the effects of urbanisation. For example, urbanisation may not affect peak discharge, flood depth, extent and velocity significantly, but rapid channel encroachment or the concentration of planned and unplanned developments in flood plains could increase flood risk significantly due increased exposure of receptors. Again, findings in this study suggests that planning and management of flood-risk could be better understood at the sub-basin scale than watershed scale given that hydrologic response to urbanisation is more obvious when studied at subbasin scale.

8.3 Academic contribution.

1. This study extends understanding of historical land-use dynamics in the studied area from a local/municipal scale to regional scale, which captures watershed scale changes that has implications for the regional hydrology. The findings of this study establishes that urbanisation is the key driving force of land-use change at the watershed scale. In terms of the extent of change, it reveals that urban growth quadrupled in extent between 1986 and 2003 (Table 5.1), which was previously underestimated.

2. This study have furthered understanding on the process of change in the watershed by showing that the transition to urban land category was dominated by net changes (i.e.

changes in quantity). It also revealed that although there was considerable loss of agricultural land, and the process of change was dominated by swap changes (i.e. changes in location), see Table 5.8. Estimation of net changes without the swap component does not present the full picture of the overall landscape change. It underestimates it.

3. This study has improved understanding by showing that historical changes in maximum peak flow were substantial at a watershed scale. It increased by about 68% between 1986 and 2003, bearing in mind that results of historical changes were presented with some uncertainties due to possible errors from classification, and input data quality.

4. I also furthered understanding by showing that future changes in annual maximum peak flow could be more significant at watershed scale, i.e. about 182% increase from 1986 and about 68% from 2003 in the event of a 100yr storm flood. Again, there are some uncertainties with the results, which could be due to errors resulting from digitisation, combination of multi-source data and assumptions made.

5. The study also extends knowledge by revealing that the impact on runoff is largely attributed to climate change in this watershed. Like in the past, the study reveals future urbanisation is likely to have little or no impact on the annual maximum peak flow at the watershed scale; however, urbanisation is projected to have considerable impact on peak flow in a number of subbasins, which may lead to frequent flash flooding in these subbasins.

6. This study has likewise furthered understanding on the hydrologic effect of forest in the GPH watershed. Like urbanisation, this study found that afforestation could have little or no impact on future annual maximum peak flow when assessed at watershed scale (Figure 6.7a). It has shown that the effects of forest on runoff varies in a number local subbasins (Figure 6.7b)

7. Based on the model results, I found that the Bori and Omoku/Ogba location alternative would have been the most and least disruptive respectively in terms of hydrological impact (Figure 6.9). The location of impermeable surfaces (whether upstream or downstream) had little or no impact on runoff at subbasin and basin scales.

8. I found that climate change is the main driver of change in the magnitude of flood hazard in the river channels and floodplains of the study area. The study found that rainfall could have significant effect on flood hazard (Table 7.1 and 7.2) while urbanisation is likely to have little or no effect.

9. The study found that important infrastructure that could be affected by future flood hazard include the two Port-Harcourt seaports and their installations, the Onne seaport and its installations, the University of Science and Technology (Figure 7.37). I also found that about 37km of roads in the area could be affected by a 100yr storm flood. Moreover, approximately 8.1km and 198m of the road and rail network (Figure 7.38 and 7.40) are more at risk of flooding by means of their exposure to floods with very high damage potential.

10. Priority areas in the GPH plan are located in the south (Phase 3 area), consisting of the proposed Air force base and the proposed residential area near Onne seaport.

11. My main contribution to knowledge is that despite the high rate of urbanisation in the GPH watershed, the impact of urbanisation on flooding in the GPH watershed is not significant which could be attributable to the size of the storm and watershed based on the model and data used. Nevertheless, urbanisation is still likely to increase flood risk due to greater exposure of elements in the flood plains to very high damaging floods.

8.4 Limitation of Study.

A number of limitations resulted from the methodologies of this research. Most of which are related to the quality of the available data in this region. Overcoming these problems were time consuming, however, the underlying goal of this study was to understand the environmental changes in a data sparse environment. Some of limitations have been discussed in detail in the methodology and data chapters. This is a summary of the main points.

1. The first limitation is with the backdated remote sensing data used as baseline data. This research was intended to make use of 2009 baseline inputs for hydrological modelling and scenario analysis, however, this was not possible because of the high

cloud cover and scanner issues which affected the required data. TM maps of year 2003 was then used for analysis which does not give an accurate picture of changes due to GPH development. However, the assumption was that land use changes between 2003 and 2009 will not be significant. Moreover, using the GPH Masterplan for the 2060 land use changes is a big generalisation as other land use changes will happen in that time period.

2. Due to the scope of the study area, four remotely sensed maps were merged which made thematic classification difficult and may have affected the accuracy of the change detection result. In addition, due to the unavailability of a good truth map for the study area, the 1995 LULC map obtained from the ministry of Land and Housing was used for accuracy assessment. The accuracy of land-use change detection also rely on the quality of the truth map which in this case does not match the time periods analysed and seem to have been misclassified in some areas. This could increase uncertainty of the results, however the classified maps were acceptable because of the reliability of the method applied, and consistency with trends of prior studies and the author's knowledge of the landscape. To minimise the uncertainty arising from this, the hydrologic and hydraulic analysis performed in this study was mainly analysed for the 1986 and 2003 time periods which matched the Landsat data time periods. Importantly, the result was still acceptable because LULC classes closely match with classifications in LULC prior studies.

3. Next, a high resolution digital elevation model data was not available for this area. The only available data was the coarse 90x90m resolution DEM which produces poor vertical and a horizontal representation of channels and river beds. Coarse vertical resolution has implications for actual river depth, especially in upstream areas. In this research, upstream channels were not properly represented. Ultimately the coarse resolution data may lead to high uncertainty in the results, however, I am confident of the results, firstly, because of the performance of the model validation in chapter 6 and 7. Second, this type of data has successfully been applied in hydrologic modelling for other watersheds as documented in published work of Ndomba *et al.* (2008) and Pramanik *et al.* (2010). Very importantly, it is considered suitable for areas with low relief.

4. Again, due to the poor DEM data quality available for the study area, it was difficult for the model to route floods in upstream areas. This costed my time in dealing with errors

5. Next, attempts were made to obtain the GPHDA EIS report. But only parts of the report (Executive summary and Justification project) were released by the Authority. This was partly why I limited my research on EIA. However, the spatial information I got from the detailed summary and justification of project was sufficient to examine the impact of locational alternatives on flood.

6. Furthermore, the projects and Masterplan have already been approved. Therefore, analysis of alternatives may cause some confusion. I clearly state in this study that the outcome of this project does not have any implication on the approval of the project. The analysis of alternatives were purely used for academic purposes and this was why I made assumptions and was able to use hypothetical alternatives.

7. Besides, the combination of multi-temporal and multi-source data LULC data could increase the uncertainty of the flood model (HMS and RAS) results. Due to unavailability of data, multi-temporal (2002/2003) maps of the study area were combined to represent the entire coverage of the study area. However, this was acceptable because the maps were obtained in December of 2002 and January of 2003. That is, the difference was only by one month. Again, the analysis of future changes was performed after combining multi-source maps. Land-use classes in any of the maps could be over generalised which may affect the accuracy of the flood modelling result. Once more, error generated during digitisation (or digitisation error) of the GPHDA Masterplan layout map could increase the uncertainty of the flood model results. However, the model results were deemed acceptable after validating the model outputs with published (independent) data.

8. Lastly, observed flow data are key for improving the accuracy of models. In this study, there were no observed data available for calibrating the HEC-HMS model. However, I was able to use an alternative approach for predicting changes in runoff. The prediction in ungauged basins approach relies on basin geometry data or physical

characteristics of the basin such as channel slope, length, shape, bottom width, side slope, which are considered reliable (Feldman, 2000).

8.5 CONCLUSIONS BASED ON EVIDENCE PRESENTED.

The overall aim of this study was to understand the effects of land-use and climate changes on flooding in the Greater Port-Harcourt watershed. This study concludes that the Greater Port-Harcourt watershed has undergone significant changes in the recent decades, and is projected to undergo drastic urban land use changes by 2060 due to the implementation of the GPH Masterplan. The study concludes that the projected high rate of urbanisation could have little or no effect on annual maximum peak flow at watershed scale, rather it could have considerable impact of runoff in a number of subbasins. Urbanisation may not have a significant impact on annual maximum flow, urbanisation could increase the flood risk due to greater exposure of people, buildings and important infrastructure to flooding in floodplains. The study also conclude that climate change is the main driver of flooding in the GPH watershed, urbanisation is rather likely to cause considerable impact on runoff in local subbasins, which may lead to frequent flash floods in those local areas.

The Greater Port-Harcourt watershed has experienced substantial changes in land use/land cover over the last few decades. The dominant force of land use change in the watershed has been urbanisation. Prominent transitions include shifts from agricultural land to urban land as well as agricultural land to forest land. Conversions to urban land was the most dominant land-use change in the watershed (about $415km^2$) and about 93% of this conversion was chiefly at the expense of agricultural land. Transition to urban land mainly experienced a net change process, which implies a change in actual quantity. The loss of agricultural land was another dominant force of land-use change, however, agricultural land mainly exhibited a swap process of change, i.e. mainly relocation. This study has been used to provide new insights on the nature of change in the watershed that has not previously been reported. Reporting the net changes alone fails to capture the swapping component and underestimates the total change (Pontius *et al.*, 2004). Generally, swap change explains up to about 64%of the overall changes in this watershed. This means that more changes may have occurred in the watershed that may not have been captured in previous studies.

Climate change remains the key driving force of change in the watershed. It is likely to have significant impact on flood hazard. To minimise flood risk, this study has identified priority infrastructure to be highlighted during planning and flood risk management. They include, two Port-Harcourt seaports and their installations, Onne seaport and its installations, the cement factory near industry road, and the University Science and Technology. To curtail obstruction and hardships, greater attention should be payed to about 8.1km of approximately 37km of the Port-Harcourt road network shown in the map in Figure 7.36. This is because of the greater risk of flooding at these locations by means of their exposure to floods with very high damage potential. Priority areas for flood risk management in the proposed Masterplan are mainly in the south and includes the proposed Air force base and residential areas near Onne seaport. This study recommends the integration of structural and non-structural measure to be used for flood risk management and planning. Structural measures should mainly be applied for exiting high densities, while non-structural measures such as zoning should be used for bare areas. The sequential test approach in the PPG25 can be adopted for additional control. Ultimately, this study has demonstrated that simple methods can be used for assessing impacts and conveying important messages. It is pertinent to note that, the results (and percentages) in this study are presented with some uncertainties due to possible errors from different sources such as classification, digitisation and assumptions made in the study. While no LULC and model results is perfect, the results in this study were deemed acceptable because of the reliability of the method applied, the author's knowledge of the landscape and consistency with the trend of change when compared with results in prior studies in addition to the two flood model validations. The important points that would not be significantly affected by the uncertainties are that: (1) urban expansion was rapid; (2) the expansion could rapidly increase by 2060 due to the GPH development; (3) the rapid urban expansion occurred mainly at the expense of agricultural land; (4) climate change is the main factor affecting flood dynamics; (5) urbanisation has little or no effects, however, greater exposure of receptors could increase flood risk.

8.6 FURTHER RESEARCH

Finally, I have been able to assess the historical and potential impacts of land-use and climate change on runoff and the hydraulic condition of the watershed, however, there were a number of limitations that remain, mainly relating to data quality and methods applied. This subsection highlights some further research suggestions that would be beneficial for futher studies.

First, there is a lack of high resolution DEM data for the study area as earlier stated. The only available data was the low resolution (90mx90m) DEM data which could have implications for the accuracy of the results in terms of vertical and horizontal representation of channels and river beds. Coarse vertical resolution could misrepresent the actual river depth, especially in upstream areas. In this study, upstream channels and flood plains where most people live were not properly represented. The primary disadvantage of using low resolution DEM input data includes the loss of important small-scale features that could affect flood propagation. To provide a more accurate representation of the topography of upstream rivers and floodplains, future studies might, for example, utilise high quality airborne remote sensing data such as "Light Detection and Ranging" (LIDAR). This would be mainly beneficial for modelling topographically complex areas such as urban areas where features like roads, buildings, river banks and dykes could have significant effect on flow dynamics and flood propagation. Apart from that, accounting for such features is important for model set-up. The main benefit of acquiring LIDAR data is for accurate representation of channels, and small-scale feature on flood plains. LIDAR is also less subject to the horizontal errors inherent in using data sets derived from contour lines. Unlike SRTM, LIDAR can generate maps of surface height over large areas with a height precision of about 15 cm and spatial resolution of 1cm (Haile and Rientjes, 2005). Apart from LIDAR, data from other high-resolution satellite sensors that could be utilised include WorldViewer-4 (0.31m), GeoEye (0.46m), QuickBird (0.61m), Ikonos (0.82m) and SPOT-6 (1.5m). Data from such sensors will be beneficial for modelling small scale flood processes because in very small basins, small topographic features such as levees, dykes and ditches could impact on model results (Haile and Rientjes, 2005).

Second, the lack of cloud-free LULC baseline data was also highlighted in this research. The goal was to make use of 2009 baseline input data for hydrological and hydraulic modelling, however, this was constrained by high cloud cover and scanner issues. Instead, the 2003 Landsat map was used as baseline input but did not give an accurate picture of changes in the area. Further studies would require a representative baseline data to accurately assess changes from a specific date. Again, the acquisition of LIDAR data would be advantageous. Apart from DEM extraction, LIDAR can also be useful for real time land cover classification (Yan *et al.*, 2015). For this study area, it can be used to derive a more accurate LULC baseline data for hydrologic and hydraulic modelling purposes. For, example LIDAR can be used for deriving cloud free and real time data of percentage of impervious surfaces, slope surface, curve number and hydraulic roughness data. In addition, with the acquisition of high resolution data, high resolution distributed models could be used againt the traditional low resolution lumped model, since high resolution data reduces uncertainty.

Third, the combination of multi-source and multi-date data for forecasting future urban land-use changes and flood related changes presents additional uncertainties in the model results. In terms of the assessing future land-use changes, further improvements could be made. For example, there are a number of alternative techniques available for examining future land-use changes. For instance, than combining multi-source and multi-date data, land use models such as Cellular automata, CLUE-S and Markov models are powerful tools that can be used to for predicting land-use changes based on land-use demands and land use policy. Cellular Automata, CLUE-S and Marcov models are the most commonly used models to study land use change (Han *et al.*, 2015; Jiang *et al.*, 2015). Based on land-use demand, these models can be used for predicting future land-use changes under different scenarios. At present, LULC change models can be utilised to explore where, when and why changes occurs. It means the application of land-use change models can be useful in linking future land-use demands and the resultant impact on floods. Spatially rule-based models or explicit models such as the cellular automata model can also be used for determining the patterns and processes of LULC change. It can also for projecting the locations of future changes. Remarkably, the Markov model can be helpful in studying the direction of LULC changes and providing a framework for analysing future land use demand (Han *et al.*, 2015).

Forth, addtinional validation data are needed for improving the accuracy of land use predictions for the GPH watershedand and should be done with independent and observed data. This study have relied on alternative methods, the author's knowledge of the watershed (by visual interpretation), and limited published data for producing results for study area. In future, accuracy assessment would require good reference data for validating land-use change results. Reference or truth data in form of field survey data, single-date Google earth maps would be appropriate. In addition, high resolution imagery and ortho-rectified aerial photographs would be appropriate provided that the date of acquisition is close to date of the selected classified maps. Moreover, the comparison of reference data and classified maps can be carried out statistically using error matrices. Furthermore, rainfall-runoff models are powerful tools for predicting watershed response. However, the models are also required to be calibrated and validated to improve accuracy (Nguyen and Tran, 2010). In this study, geometric data derieved from DEM of watershed was applied as an alternative. However, in many situations conceptual models are used because thier input data are usually readily available, Moreover, the models are comparatively simple and easy to use. The model parameters are usually conceptual representations of the watershed and are determined by trial-and-error method, which involves adjusting the parameter values to match the model response to historical data (Gupta *et al.*, 1998). Apart from using the watershed's physical characteristics in poorly gauged watersheds, the regression method of regionalisation (i.e. transferring information from neighbouring catchments to the catchment of interest) can be applied to improve accuracy (Parajka *et al.*, 2005). Regionalisation based on parameters of neighbouring catchment and the kriging method are preferred over regionalisation based on a catchment's physical attributes because several studies have shown that, spatial proximity is a better alternative of unknown controls on runoff dynamics than catchment attributes (Peel *et al.*, 2000; Merz and Blöschl, 2004; Parajka *et al.*, 2005).

Aside from overcoming data limitations in this research, it is important to note that this study has bettered understanding of flood risk at the source, pathway and receptor in the GPH watershed, except the consequences. However, one important aspect that should be explored in future studies is the consequence component of the SPRC (flood risk) model. This is because research on future flood damage would better understanding of the future consequence of flood events (Messner and Meyer, 2006). Flood damage analysis typically encompass the estimation of all variety of harm in the watershed caused by flooding. Future research should consider examining a wide range of harmful effects on humans, human health and their possessions. In addition to public infrastructure, it should assess the impact on ecological systems, cultural heritage and the city's economy. Impacts could be specified in monetary (tangible) or non-monetary (intangible) terms (Messner and Meyer, 2006; Hammond *et al.*, 2012). Some data applied or derived could be useful for future flood damage research in the GPH watershed. They include topographic data, hydrologic and hydraulic model output data and building data. Importantly, depth-damage function data are very important and could be obtained from the Manual for Economic Appraisal by Penning-Rowsell *et al.* (2014). Theoretically, it would help to improve understanding of the social dynamics of flood, preparedness, vulnerability, risk perception and flood management issues in the watershed. On the other hand, estimation of future flood damage would give policy makers an idea of flood damages that could be produced by a specific flood event to help strengthen policy.

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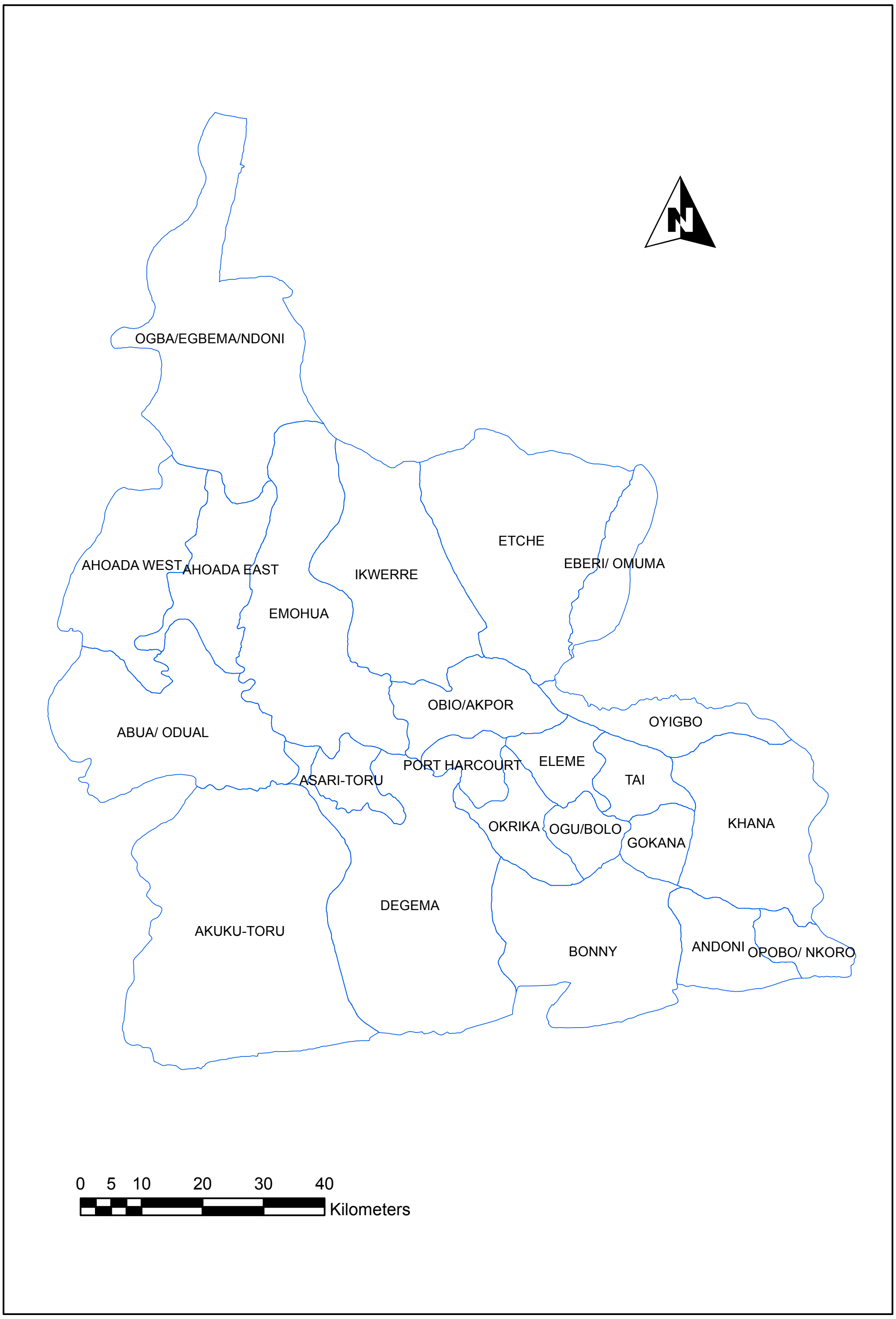
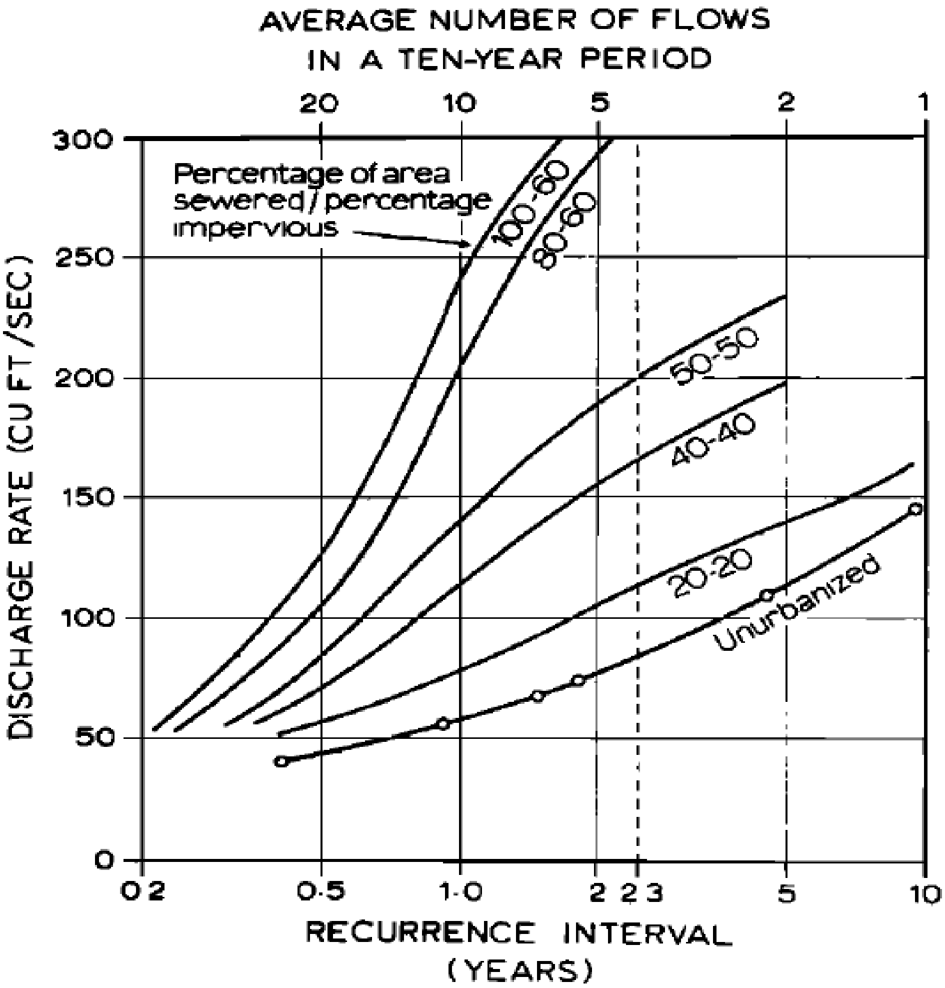
APPENDICES

Appendix 1.1 Map showing the location of Portharcourt in Rivers State. Source: Rivers State Ministry of Land and Housing.



Appendix 2.1 Graph showing the relationship between percentage of area sewered and percentage of area impervious to flood re-occurrence interval (Leopold, 1968).

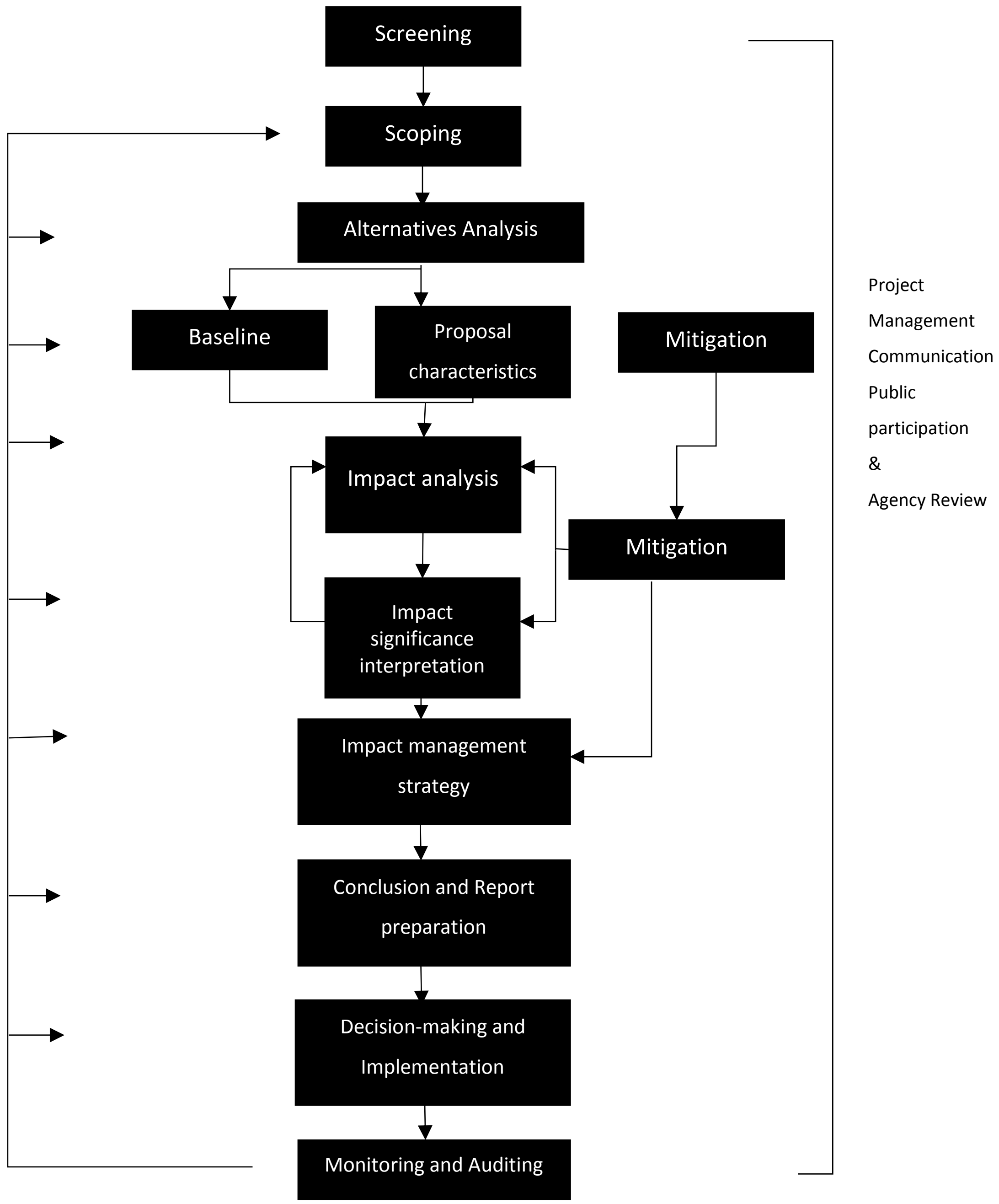


Appendix 2.2 Results of discharge ratio, percentage of impervious area and lag times from synthesis of in large number of studies in Hollis (1975).

Reference	Before and after urbanisation Discharge ratio	Percentage of imperviousness (PctImp) %	Reoccurrence interval T	Discharge	Lagtimes
Bigwood and Thomas (1955) Basin 1 and Basin 2	3	20	2.33	Increased	
	3	20	2.33	Increased	
Carter (1961)	1.8	12	2.33	Increased	
Wiltala (1965)	3	25	2.33	Increased	
James (1965)	1.4	10	2.33	Increased	
	1.3	10	5	Increased	
	1.2	10	10	Increased	
	1.2	10	25	Increased	
	1.1	10	200	Increased	
Crawford and Linsley (1966)	20	6.7	0.1	Increased	
	13	6.7	0.5	Increased	
	1.6	6.7	3	Increased	
Espey et al (1966)	3.2	21	2.33	Increased	Shortened
	5.9	50	2.33	Increased	Shortened
	4.4	27	2.33	Increased	Shortened
	6	50	2.33	Increased	Shortened
Wilson (1967)	1.9	9	2.33	Increased	
	2.2	11	2.33	Increased	
	2.8	18	2.33	Increased	
	3.6	27	2.33	Increased	
Anderson (1967)	2.86	20	2.33	Increased	
	2.35	20	25	Increased	
	2.24	20	50	Increased	
	2.2	20	100	Increased	
	3.85	50	2.33	Increased	
	2.61	50	25	Increased	
	2.36	50	50	Increased	
	2.2	50	100	Increased	
Kinosta and Sonda (1969)	2e	44.3	100	Increased	
Curtis et al. reported by American Society of Civil Engineers task Force on Effect of Urbanisation on Flood Discharge (1969)	1.5	15	10	Increased	
	1	15	100 (+)	Increased	
U.S Geological Survey study of Little Sugar Creek, North Carolina (reported by American Society of Civil Engineers task Force on Effect of Urbanisation on Flood Discharge (1969)	1.6	15	2.3	Increased	
	1.3	15	10	Increased	
	1.2	15	20	Increased	
Shaw and Waller (1973)	10	20	1(+)	Increased	
Hammer (1973)	2.5	25	1.5	Increased	

	2.2	25	2.33	Increased	
	2	25	5	Increased	
	1.9	25	10	Increased	
	1.8	25	20	Increased	
	1.7	25	50	Increased	
	4.3	25	1.5	Increased	
	3.5	50	2.33	Increased	
	3	50	5	Increased	
	2.8	50	10	Increased	
	2.6	50	20	Increased	
	2.5	50	50	Increased	
	3.3	25	1.5	Increased	
	2.9	25	2.33	Increased	
	2.6	25	5	Increased	
	2.4	25	10	Increased	
Puntam (cited by Hammer (1973)	2.2	25	20	Increased	
	2	25	50	Increased	
	4.2	50	1.5	Increased	
	3.7	50	2.33	Increased	
	3.2	50	5	Increased	
	2.9	50	10	Increased	
	2.6	50	20	Increased	
	2.3	50	50	Increased	
	1	16.6	20	Increased	
Graf (1977)				increased	Shortened

Appendix 2.3 Example of an EIA Process (Lawrence, 2003).



Appendix 2.4 General Principles of Environmental Impact Assessment in the Nigerian EIA Decree 86 (FGN, 1992a).

1. The objectives of any environmental Impact assessment (hereafter in this Decree referred to as "the Assessment") shall be -

(a) to establish before a decision taken by any person, authority corporate body or unincorporated body including the Government of the Federation, State or Local Government intending to undertake or authorise the undertaking of any activity that may likely or to a significant extent affect the environment or have environmental effects on those activities shall first be taken into account;

(b) to promote the implementation of appropriate policy in all Federal Lands (however acquired) States and Local Government Areas consistent with all laws and decision making processes through which the goal and objective in paragraph (a) of this section may be realised;

(c) to encourage the development of procedures for information exchange, notification and consultation between organs and persons when proposed activities are likely to have significant environmental effects on boundary or trans-state or on the environment of bordering towns and villages.

2. (1) The public or private sector of the economy shall not undertake or embark on public or authorise projects or activities without prior consideration, at an early stages, or their environmental effects.

(2) Where the extent, nature or location of a proposed project or activity is such that is likely to significantly affect the environment, its environmental impact assessment shall be undertaken in accordance with the provisions of this Decree.

(3) The criterion and procedure under this Decree shall be used to determine whether an activity is likely to significantly affect the environment and is therefore subject to an environmental impact assessment.

(4) All agencies, institutions (whether public or private) except exempted pursuant to this Decree, shall before embarking on the proposed project apply in writing to the Agency, so that subject activities can be quickly and surely identified and environmental assessment applied as the activities being planned.

3. (1) In identifying the environmental impact assessment process under this Decree, the relevant significant environmental issues shall be identified and studied before commencing or embarking on any project or activity covered by the provisions of this Decree or covered by the Agency or likely to have serious environmental impact on the Nigerian environment.

(2) Where appropriate, all efforts shall be made to identify all environmental issues at an early step in the process.

4. An environmental impact assessment shall include at least the following minimum matters, that is -

(a) a description of the proposed activities;

(b) a description of the potential affected environment including specific information necessary to identify and assess the environmental effects of the proposed activities;

(c) a description of the practical activities, as appropriate;

(d) an assessment of the likely or potential environmental impacts on the proposed activity and the alternatives, including the direct or indirect cumulative, short-term and tong-term effects:

(e) an identification and description of measures available to mitigate adverse environmental impacts of proposed activity and assessment of those measures;

(f) an indication of gaps in knowledge and uncertainly which may be encountered in computing the required information:

(g) an indication of whether the environment of any other State, Local Government Area or areas outside Nigeria is likely to be affected by the proposed activity or its alternatives;

(h) a brief and non-technical summary of the information provided under paragraph (a) to (g) of this section.

5. The environmental effects in an environmental assessment shall be assessed with a degree of detail commensuration with their likely environmental significance.

6. The information provided as of environmental impact assessment shall be examined impartially by the Agency prior to any decision to be made thereto (whether in favour or adverse thereto).

7. Before the Agency gives a decision on an activity to which an environmental assessment has been produced, the Agency shall give opportunity to government agencies, members of the public, experts in any relevant discipline and interested groups to make comment on environmental impact assessment of the activity.

8. The Agency shall not give a decision as to whether a proposed activity should be authorised or undertaken until appropriate period has elapsed to consider comments pursuant to sections 7 and 12 of this Decree.

9. (1) The Agency's decisions on any proposed activity subject to environmental impact assessment shall -

(a) be in writing;

(b) state the reason therefor;

(c) include the provisions, if any, to prevent, reduce or instigate damage to the environment.

(2) The report of the Agency shall be made available to interested person or group.

(3) If no interested person or group requested for the report, it shall be the duty of the Agency to publish its decision in a manner by which members of the public or persons interested in the activity shall be notified.

(4) The Council may determine an appropriate method in which the decision of the Agency shall be published so as to reach interested persons or groups, in particular the originators or persons interested in the activity subject of the decision.

10. When the Council deems fit and appropriate, a decision on an activity which has been subject of environmental impact assessment, the activity and its effects on the environment or the provisions of section 9 of this decree shall be subject to appropriate supervision.

11. (1) When information provided as part of environmental impact assessment indicates that the Environment within another State in the Federation or a Local Government Area is likely to be significantly affected by a proposed activity, the State, the Local Government Area in which the activity is being panned shall, to the extent possible -

(a) notify the potentially affected State or Local Government of the proposed activity;

(b) transmit to the affected State or Local Government Area any relevant information of the environmental impact assessment:

(c) enter into timely consultations with the affected State or Local Government.

(2) It shall be the duty of the Agency to see that the provisions of subsection (1) of this section are complied with and the Agency may cause the consultations provided pursuant to

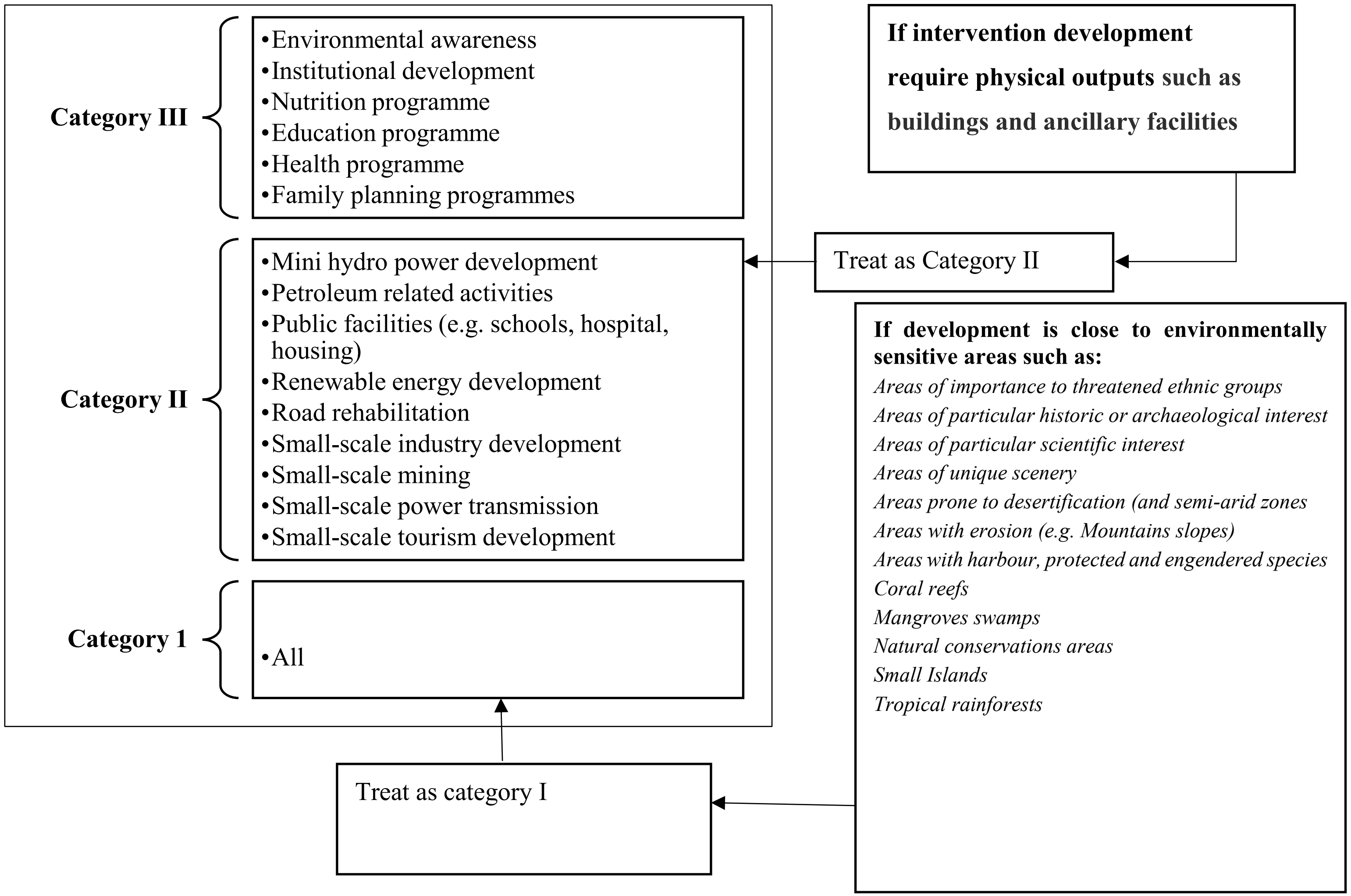
subsection (1) of this section to take place in order to investigate any environmental derogation or hazard that may occur during the construction or process of the activity concerned.

12. Editorial Note: there is no section 12 within this Decree.

13. (1) When a project is described on the Mandatory Study List specified in the Schedule to this Decree or is referred to mediation or a review panel, no Federal, State or Local Government or any of their authority or agency Shall exercise any power or perform any duty or functions that would permit the project to be carried out in whole or in part until the Agency has taken a cause of action conducive to its power under the Act establishing it or has taken a decision or issue an order that the project could be carried out with or without conditions.

(2) Where the Agency has given certain conditions before the carrying out of the project, the conditions shall be fulfilled before any person or authority shall embark on the project.

Appendix 2.5 Categorisation of projects and programmes in the Nigerian EIA (FEPA, 1994).



Appendix 2.6 List of category 1 or mandatory projects in EIA Decree 86. Regulation, Source (FGN, 1992a).

Mandatory category of development	Extent/Capacity/Size
1. AGRICULTURE	
(a) Land development schemes involving conversion of forest and into agricultural production.	5000 hectares
(b) Agricultural programmes necessitating the resettlement	≥ 100 families
(c) Development of agricultural estates involving changer in type of agricultural use.	5000 hectares
2. AIRPORT	
(a) Construction of airports having with airstrip	≥ 2,500 metres
(b) Airstrip development in State and national parks.	All
3. DRAINAGE AND IRRIGATION	
(a) Construction of dams and man-made lakes and artificial enlargement of lakes with surface areas	≥ 200 hectares
(b) Drainage of wetland, wild-life habitat or of virgin forest	≥100 hectares
(c) Irrigation schemes	≥ 5,000 hectares
4. Land Reclamation	
(a) Coastal reclamation	≥50 hectares
5. FISHERIES	
(a) Construction of fishing harbours.	All
(b) Harbour expansion involving an increase of 50 per cent or more in fish landing capacity per annum.	All
(c) Land based aquaculture projects accompanied by clearing of mangrove swamp forests	≥ 50 hectares or more.
6. FORESTRY	
(a) Conversion of hill forest land to other land use	≥50 hectares
(b) Logging or conversion of forest land to other land use within the catchment area of reservoirs used for municipal water supply, irrigation or hydro power generation or in areas adjacent to state and national parks and national marine parks.	All
(c) Logging covering an area	≥500 hectares
(d) Conversion of mangrove swamps for industrial, housing or agricultural	≥ 50 hectares
(e) Clearing of mangrove swamps on islands adjacent to national marine parks.	All
7. HOUSING	All
8. INDUSTRY	
(a) Chemical	All
Where production capacity of each product or of combined products	≥100 tonnes/day
(b) Petrochemicals all sizes.	All
(c) Non-ferrous primary smelting	All
Aluminium	All sizes
Copper - all sizes	All sizes
Others - producing	≥ 50 tonnes/day
(d) Non-metallic	All

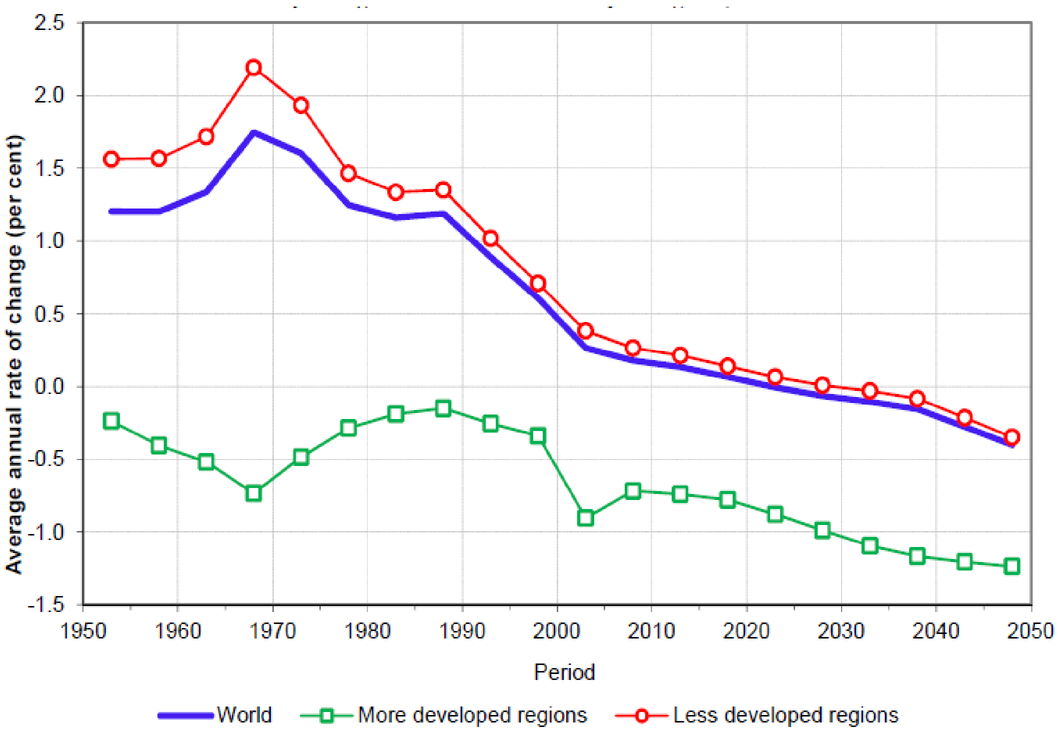
Mandatory category of development	Extent/Capacity/Size
- Cement - for clinker throughput	≥30 tonnes/hour
- Lime -	100 tonnes/day and above burnt lime rotary kiln or 50 tonnes/day and above vertical kiln.
(e) Iron and steel	All
- Require iron ore as raw materials for production	≥100 tonnes/day
- Using scrap iron as raw materials for production	≥ 200 tonnes per day.
(f) Shipyards	All
- Dead Weight Tonnage	≥ 5000 tonnes.
(g) Pulp and paper industry	
- Production capacity	≥ 50 tonnes/day
9. INFRASTRUCTURE	
(a) Construction of hospitals with outfall into beachfronts used for, recreational purposes.	All
(b) Industrial estate development for medium and heavy industry	≥ 50 hectares
(c) Construction of Expressways.	All
(d) Construction of national highway.	All
(e) Construction of new townships.	All
10. Ports	
(a) Construction of ports.	All
(b) Port expansion	≥ 50 percent or more in handling capacity per annum.
11. MINING	
(a) Mining of materials in new areas	≥ 250 hectares.
(b) Ore processing, including concentrating for aluminium, copper, gold or tantalum.	All
(c) Sand dredging	≥ 50 hectares
12. PETROLEUM	
(a) Oil and gas field development.	All
(b) Construction of off-shore pipelines	≥50 kilometres
(c) Construction of oil and gas separation, processing, handling, and storage facilities.	All
(d) Construction of oil refineries.	All
(e) Construction of product depots for the storage of petrol, gas or diesel (excluding service stations) which are located within 3 kilometres of any commercial, industrial or residential areas and which have a combined storage	≥ 60,000 barrels or more.
13. POWER GENERATION AND TRANSMISSION	
(a) Construction of steam generated power stations burning fossil fuels	≥10 megawatts.
(b) Dams and hydroelectric power schemes with either or both of the following.	All
(i) dams	≥15meters high
(ii) ancillary structures covering	≥ 40 hectares
(iii) reservoirs with a surface area in excess of	≥ 400 hectares;
(c) Construction of combined cycle power stations.	All
(d) Construction of nuclear-fuelled power stations.	All
12. QUARRIES	

Mandatory category of development	Extent/Capacity/Size
(a) Proposed quarrying of aggregate, limestone, silica, quartzite, sandstone marble and, decorative building stone	Within 3 kilometres of any existing residential, commercial or industrial areas, or any area for which a licence, permit or approval has been granted for residential, commercial or industrial development
15. RAILWAYS	
(a) Construction of new routes.	All
(b) Construction of branch lines.	All
16. TRANSPORTATION	
17. Resort and Recreat1onal Development	All
(a) Construction of coastal resort-facilities or hotels	≥ 80 rooms.
(b) Hill station resort or hotel development	≥50 hectares
(c) Development of tourist or recreational facilities in national parks.	All
(d) Development of tourist or recreational facilities, on islands in surrounding waters which may be declared as national marine parks.	All
18. WASTE TREATMENT AND DISPOSAL	
(a) Toxic and Hazardous Waste	All
(i) Construction of incineration plant.	All
(ii) Construction of recovery plant (off-site)	All
(iii) Construction of waste water treatment plant (off-site).	All
(iv) Construction of secure landfill facility.	All
(v) Construction of storage facility (off-site).	All
(b) Municipal Solid Waste	All
(i) Construction of incineration plant.	All
(ii). Construction of composing plant.	All
(iii) Construction of recovery/recycling plant.	
(iv) Construction of municipal solid waste landfill facility.	All
(c) Municipal Sewage	All
(i) Construction of waste water treatment plant.	All
(ii) Construction of marine outfall.	All
19. WATER SUPPLY	
(a) Construction of dams, and impounding reservoir	≥ 200 hectares
(b) Groundwater development for industrial, agricultural or urban water supply	≥,500 cubic metre/day

Appendix 2.7 List of Federal Environmental Protection Agency sectoral EIA guidelines for different sectors. Source: FEPA, (1994).

Sectoral projects
1. Agricultural and Rural Development
2. Agricultural land management
3. Chemicals and allied Industries.
4. Coastal development
5. Dams and reservoirs
6. Drainage and irrigation
7. Dredging
8. Extraction and beneficiation
9. Flood management
10. Infrastructure
11. Manufacturing
12. Oil and gas exploration and production (off-shore)
13. Oil and gas exploration and production (on-shore)
14. Petrochemicals
15. Petroleum and Petrochemicals
16. Petroleum refining
17. Pipeline construction
18. Roads and highways
19. Solid Mineral Mining and Development
20. Urban development

Appendix 3.1 Average annual rate of change of the rural populations in the world, (UNDESA, 2015).



Appendix 3.2 Table showing percentage of changes in land-use in the Port-Harcourt between 1986 and 1996 Source: Mmom and Fred-Nwagwu (2013).

LULC	Area in km^2 1986-1996	Percentage
Farm land to Vegetation	9240.3	10.31
Vegetation to vegetation	23060	25.72
Farmland to residential Area	2700	3.01
Vegetation to Farmland	2241.0	2.50
Farmland to Farmland	803.8	0.90
Vegetation to Residential area	6349.8	7.08
Residential area to residential area	9953.9	11.10
Swamp to Residential area	3.6	0.004
Residential Area to vegetation	1626.3	1.81
Farmland to water body	45.9	0.05
Vegetation to swamp	490.23	0.55
Swamp to swamp	891.45	0.99
Swamp to Swamp	20420.19	22.78
Swamp to waterbody	2631.96	2.94
Farmland to swamp	640.8	0.71
Residential area to farmland	339.84	0.28
Vegetation to water body	43.47	0.05
Swamp to residential area	686.07	0.77
Residential Area to swamp	182.52	0.20
Water body to Water body	7067.07	7.88

Appendix 3.3 Trends and rate of changes in land use and land cover in Portharcourt Mmom and Fred-Nwagwu (2013). Urban area increased by 473% between 186 and 2007.

LULC Type	1986-1996		1996-2007		1986-2007	
	Area km^2	% change	Area km^2	% change	Area km^2	% change
Water bodies	1012.41	-10.26	-1625.67	-18	2638.08	-125.62
Residential	8518.8	73	1432.25	7	9951.03	473.85
Vegetation	3546.83	11	7078.36	20	10625.19	505.96
Swamp	-1923.37	-8	3649.91	-16	5573.28	265.39
Farmland	-9129.85	-71	3235.01	-88	-12364	588.8

Appendix 3.4 Construction and Operation activities of the Phase-1A Project. Project that could have impact on land cover and flood included the 3000 housing units, the sports village and the roads.

Project Type	Project Activities
Low/medium, high density mix use developments	3,000 housing units New Rivers State University of Science and Technology development Sports village 1,000 Bed mega hospital complex
Power	Power transmission ((132kV double circuit) and sub-station (132/33/11kV 100MVA) and reticulation system
Water	Bulk water abstraction, storage and supply system;
Sports	18 hole Golf course with signature apartments on 0.87km2 of land
Roads	Priority Road and internal street network
Waste Water	Waste water management plant and reticulation system
Storm Water	Storm water drains and reticulation
Sewage	Sewage management plant and reticulation
Total Phase-1A Area	Between 7.23 and 7.50km2

Appendix 3.5 Details of Project Activity for the Phase-1A Development. Project activity includes Power construction Generation, Transmission and Distribution, Bulk Portable Water Supply Infrastructure, utility Substation Location ERML (2009).

Project Activity Type	Description
Power Generation, Transmission and Distribution	The electricity supply works for the Phase-1A project comprises the electrical transmission line and substation infrastructure required for this phase of the project. The default source of electricity for the Phase1A is connection to the existing grid of the Power Holding Company of Nigeria (PHCN) at a substation near Rumuosi. A back up diesel generator with a capacity of 3 Mega Watts (MW) shall however be provided at a location close to the Phase-1A boundary limits. For the purpose of this EIA, this location is called the utility substation and is discussed later. The utility substation shall also house the borehole and water treatment plant for the Phase-1A project scope. The electrical system sub-project includes the design, construction and operation of: • 132 KV double circuit transmission line with all associated civil, electrical, mechanical and all transmission infrastructure earth works. Double circuit towers shall be used for stringing the conductors proposed for power transmission in this project. A double circuit tower is a self-supporting structure, where specific high voltage (132KV or more) lines can be supported comfortably. Double-circuited tower means that the transmission structure (Tower) is carrying two sets of transmission lines, each with three conductors; • A 132/33/11 KV 100MVA Phase-1A substation together with associated substation distribution facilities and earth works. The goal of this initial phase is to put in place electrical transmission and distribution infrastructure for the proposed new 3,000 housing units of the New City Development Area. Support and ancillary facilities to be installed include: four (4) transformer bays; one (1) control room; one (1) switchgear room; and control cable installation; fibre optic line installation; all protection, metering and telecommunication equipment installations; all terminations, cable trenches, ducts, all Medium Voltage (MV) switchgear, Low Voltage (LV) panels, all necessary auxiliary supplies, fire protection, ablution facilities, fencing gates, access roads, lighting, line profiling, tower spotting and design, tower erection, foundation excavation, tower installation, conductor stringing and tensioning and the commissioning of all plants.
Bulk Portable Water Supply Infrastructure	The proposed Water Supply project is designed to provide a temporary water supply to the Phase-1A of the New City with a designed life of less than 5 years. Though the estimated Average Daily Demand (ADD) is about 2.5Ml/day, the distribution system is planned for ultimate capacity. With high water losses anticipated, the abstraction and treatment facilities are designed to treat 3.0Ml/day GPHCDA intention to attract development and investment into the Phase-1A area of the New City is the main driver for the temporary water supply infrastructure. The main elements of the bulk water supply project comprise of the following: - Two (2) 3Ml/d duty standby abstraction equipped boreholes located on site; - A 500 kl effective capacity pressed galvanized steel raw water contact reservoir with associated valve work, representing 4 hours of ADD storage; - A batch calcium hypochlorite (HTH) make-up and dosing plant; - An equipped pump and pressure filtration station;

- Inter-connecting pipework and valve chambers;
- A control room;
- A standby electrical generator; and
- Filter backwash water residue lagoon.

The project area experiences a high annual rainfall (over 2500mm per annum) which provides the area with ample supply of relatively fresh water from deep underground aquifers. This water source is deemed more adequate considering the very high quality of water obtained from the lower aquifers which are generally free of pollutants (especially salinity) and exploitation thereof has low environmental impact with excellent sustainability.

A new potable water treatment system is required to serve the Greater Port-Harcourt City. The works shall be constructed in stages. The first stage shall be for 50 Ml/d, and shall then be doubled up to 100 Ml/d, and then doubled up again to 200 Ml/d. The ultimate capacity for both the new and old city shall be about 800 Ml/d.

From previous studies the water in the Delta has traditionally not required any complex treatment processes and is often used without chemical treatment. However iron may be present in concentrations sufficient to require removal.

The water treatment process for the project has been selected based on type of application, the nature of groundwater treatment requirements, and the ground water physio-chemical characteristics. Treatment will include:

- Inlet works
- Aeration
- Water pre-Chlorination
- Filtration; and
- Final disinfection

A cold formed pressed steel nominal 500kl tank shall be provided to accommodate raw water storage and retention time of approximately 4 hours prior to filtration. The raw water shall be pre-chlorinated to assist in the precipitation of iron and manganese.

The duty borehole shall feed directly into the raw water tank and shall be controlled automatically between high and low water levels. The steel tank methodology is adopted specifically to accommodate the temporary nature of the facility, which can be easily disassembled and reutilized by the GPHDCA for a number of other uses in the future once the bulk water supply is operational.

The tank is to be elevated above ground level on concrete plinths for ease of access and maintenance, and is to be founded on a reinforced concrete raft. Water from the bulk system shall connect to the Phase-1A reticulation network via approximately 400m length of 450mm diameter bulk pipeline, with a single clear water valve and meter chamber beyond the treatment works. It is envisaged that the 450mm diameter bulk line shall run within the existing main road servitude, and that no specific water line servitude shall be required.

Utility Substation Location

A utility substation shall be constructed immediately south of the fence line of the Phase-1A housing estate (Figure 3-5). The utility substation is where the following facilities shall be installed and operated:

- The electricity substation for the Phase-1A scope here covered;
- The borehole for the water supply to the estate;
- The water treatment plant including required storage facilities;
- The 3MW back-up generator.

The approximate area of the utility substation is about 10,000m^2. The area is covered by shrubs and other secondary vegetation. There are no farming activities within the area.

Priority Roads

The Priority roads to be constructed as part of the Phase-1A Scope include:

- The North -South Link Road (M1)
- The University Road (M10)
- The Sports Precinct Road

The North South Link Road (M1) and University Road (M10) have been combined in one design to ease the design process. Together, they are about 8km long. The M10 starts in the west at the newly constructed Spine Road. The interface of the M10 and the Spine Road in future shall consist of a grade separated interchange. In the interim, the traffic volumes envisaged are very low and an at-grade intersection with a T-junction configuration shall be provided. The cross section of the road makes provision for a four lane configuration, which shall provide 2 lanes per direction. From the intersection with the Spine Road, the alignment of the M10 runs in an easterly direction and shall provide a number of access points into the new University Precinct.

The road alignment then changes direction to be in a generally northern direction. This section then starts the section of the road known as the North – South Link Road (M1). The cross section of the road is similar to the section of the M10. After the alignment has passed the intersection with the Boulevard Road the cross section changes such that it shall be possible in future to provide a bus rapid transport system (BRT) including stops. The cross section of the M10 makes provision for a four lane configuration which provides two lanes per direction. It terminates at the existing Ikwerre Road in the north with an at-grade intersection.

The Sports Precinct Road starts in the west with a full intersection with the North South Link Road. This road generally runs in an east west direction to the north of the proposed new sport complex. The Sports Precinct Road shall provide access to the new sport complex. The cross section of this road makes provision for a four lane configuration which shall provide two lanes per direction. The Sports Precinct Road ends just east of the last access point into the proposed new Sports Precinct.

Housing Estate and Internal Township Services

The Phase-1A scope covered by this EIA includes the provision of housing estate internal services. These consist of facilities or infrastructure designed to service the housing units and other land use purposes planned for the Phase-1A development of the Greater Port-Harcourt City. The internal services comprise:

- Internal water reticulation network, a network of u-PVC pressure pipes ranging in size of 110mm diameter to 500mm diameter of potable water in the new development with a connection to each plot;
- Internal sewer drainage network, a network of u-PVC sewer pipes ranging from 160mm diameter to 400mm diameter for collecting and draining the sewage from the area to the bulk sewer pipes, a connection to each plot shall also be provided;
- Internal storm water network, a network of concrete pipes ranging in size from 450mm diameter for draining the storm water from the project area into the bulk storm water canals;
- Internal road construction and street lighting;
- Solid waste management facility, a facility for collection and transferring waste onto large vehicles to be disposed of at the appropriate disposal sites;
- Internal electricity reticulation network, an underground network of electrical cables to distribute electricity in the project area.

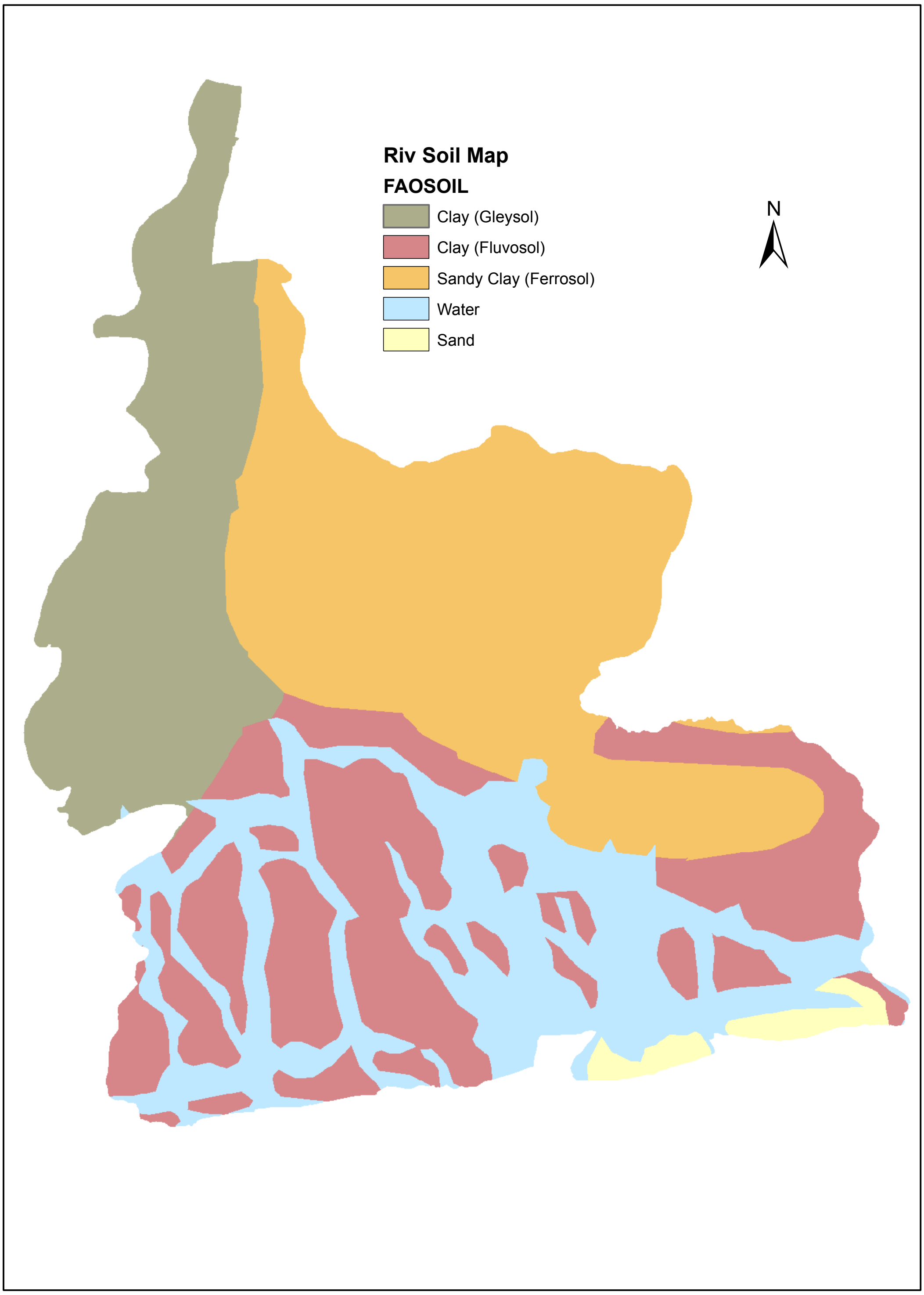
It’s important to note that all these services, except the waste management facility shall be located in the street reserves and only the road reserves and the plot for the waste management facility shall be cleared for the provision of the services.

All the services shall be provided to the various land use areas including mixed use plots through a network that is routed along the internal roads for the most part. One side of the roads shall be used for water and sewer reticulation while the electricity reticulation shall be on the other side of the road.

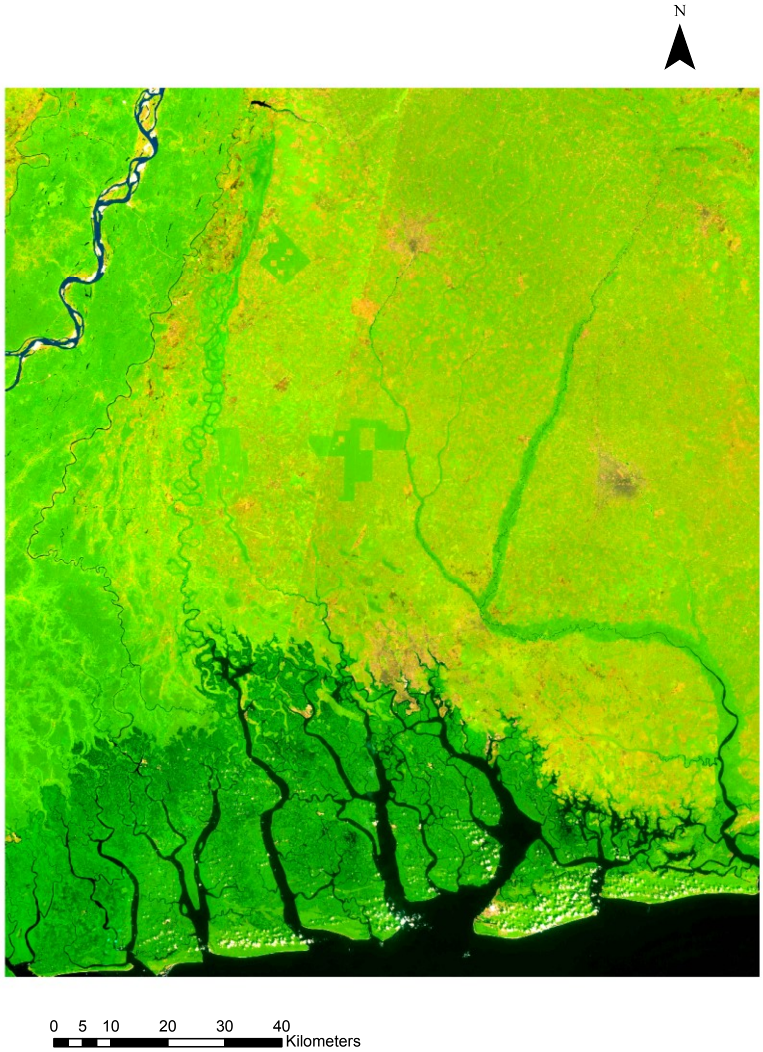
Waste Management	The GPHCDA shall implement a waste management plan for all phases of the proposed development. The plan includes identification, quantification and disposal options in accordance with regulator-approved processes and technology. The GPHCDA WMP will ensure: • All work sites are kept clean, neat and tidy at all times. • No burying or dumping of any waste materials, vegetation, litter or refuse on site. • The provision of sufficient bins (preferably vermin and weatherproof) at the camp and work sites to store the solid waste produced on a daily basis. • The collection of refuse and waste generated in work areas on a daily basis. • The identification of appropriate and/or approved temporary waste site for waste generated during the construction phase. • The final disposal of the site waste at an approved landfill site • A litter control plan for the construction and other project phases • The use of refuse screens at runoff concentration points from large parking facilities, wash bays, storm water outlets, inlets to detention ponds, workshop forecourt drainage points, ablution and eating areas. • Wherever possible, recycling of waste materials used or generated • Provision of responsible management options for any hazardous waste generated during the various project phases.

Appendix 4.1 Photographs showing some site activities and impacts. A-Construction of new stadium; B-Completed GPH road C-New Tam David-West road development; D-Proposed site for development; E-Construction of link road to stadium; F-Construction of drainage for storm water reticulation. Photograph was taken in May of 2013.

Appendix 4.2 A 1:600,000 clipped Digital Soil Map of the World for the Entire Rivers State covering the Study Area (FAO, 2007).



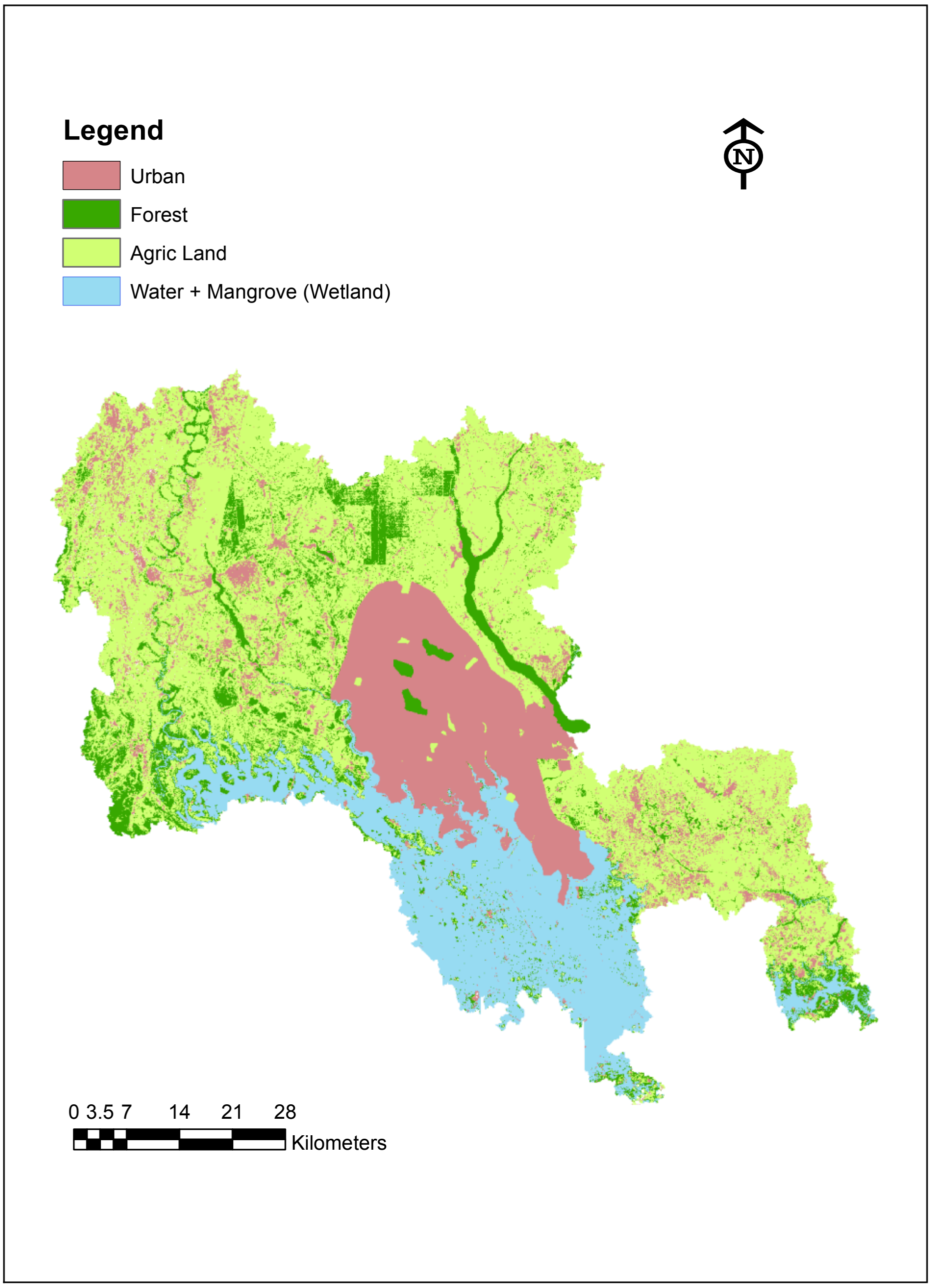
Appendix 4.3 Enhanced Thematic Mapper Imagery obtained for year 2003 (Source: USGS).



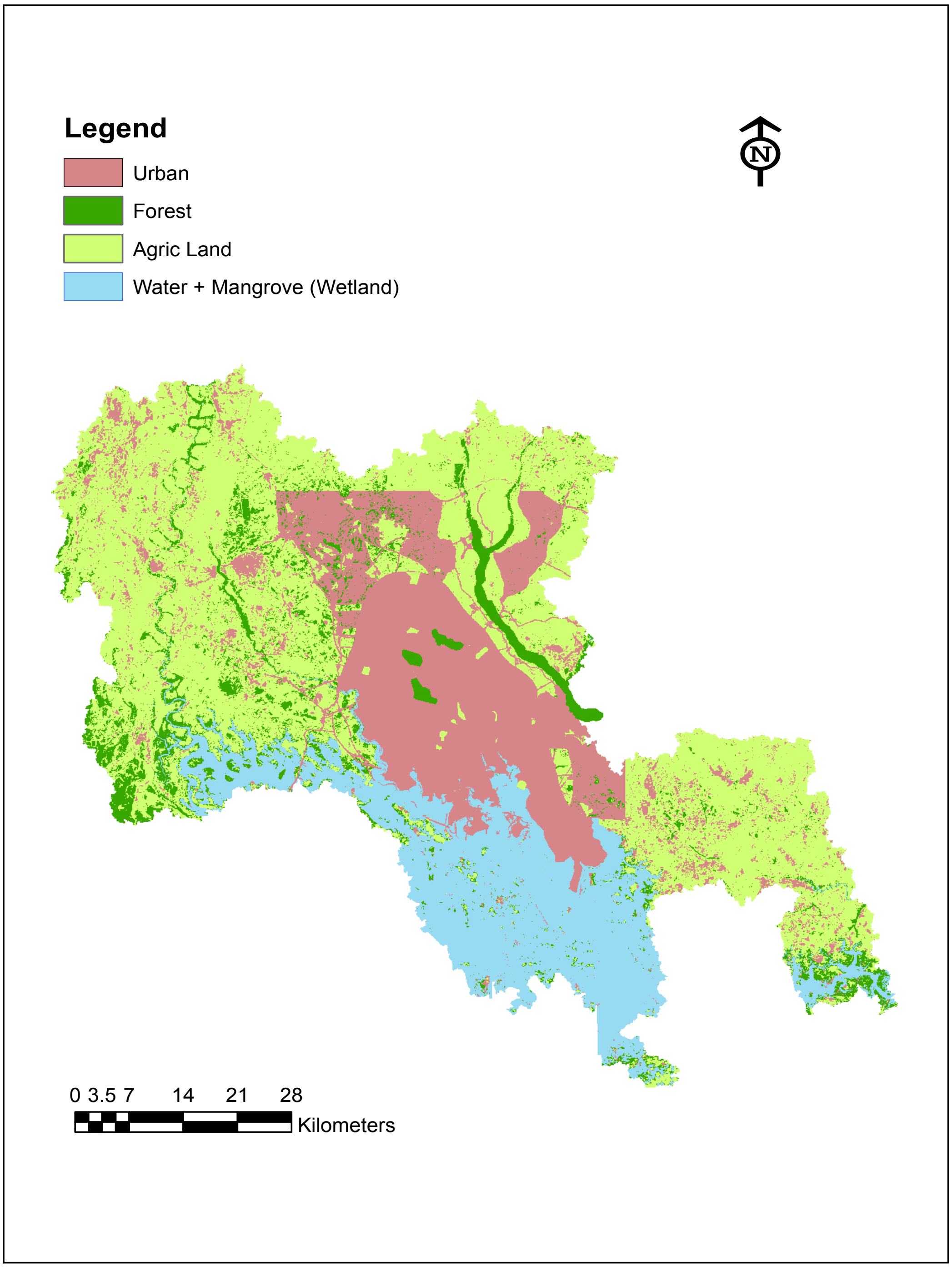
Appendix 4.4 Showing Values of Storm Probability of Occurrence and Return Period.

Year	Rainfall (mm)	Rank (n)	Probability of occurrence (Fa in %)	Return Period (T)
2002	1	185.3	2.083333	48
2003	2	173.4	6.25	16
1993	3	133.8	10.41667	9.6
2009	4	133.4	14.58333	6.857143
1998	5	132.8	18.75	5.333333
1997	6	131.8	22.91667	4.363636
2006	7	129.6	27.08333	3.692308
2007	8	128.5	31.25	3.2
1994	9	128.4	35.41667	2.823529
1995	10	126.7	70689.62	0.001415
1992	11	119.4	43.75	2.285714
2012	12	112.5	47.91667	2.086957
2010	13	111.3	52.08333	1.92
1990	14	103.5	56.25	1.777778
2001	15	96.3	60.41667	1.655172
2000	16	93.2	64.58333	1.548387
1991	17	92.9	68.75	1.454545
2004	18	83.3	72.91667	1.371429
2013	19	80.9	77.08333	1.297297
1999	20	80.5	81.25	1.230769
2008	21	80.3	85.41667	1.170732
1996	22	76.8	89.58333	1.116279
2005	23	72.4	93.75	1.066667
2011	24	68.8	97.91667	1.021277

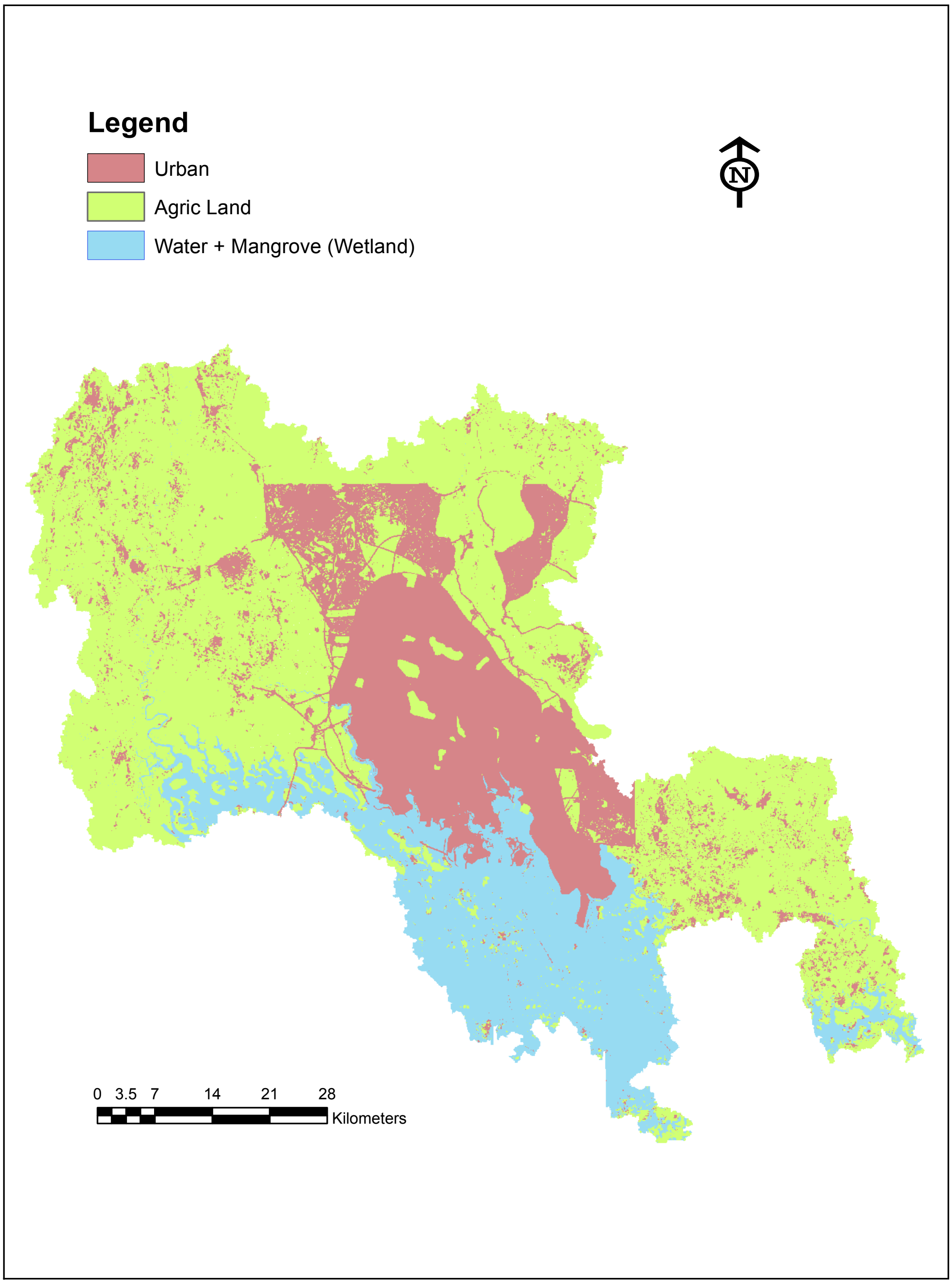
Appendix 6.1 Map showing the Urban Masterplan Scenario generated as input for hydrological modelling. The digitised Masterplan map was overlaid on the 2003 baseline map. Mangrove and water is classed as water in the HMS model due to their hydrologic properties.



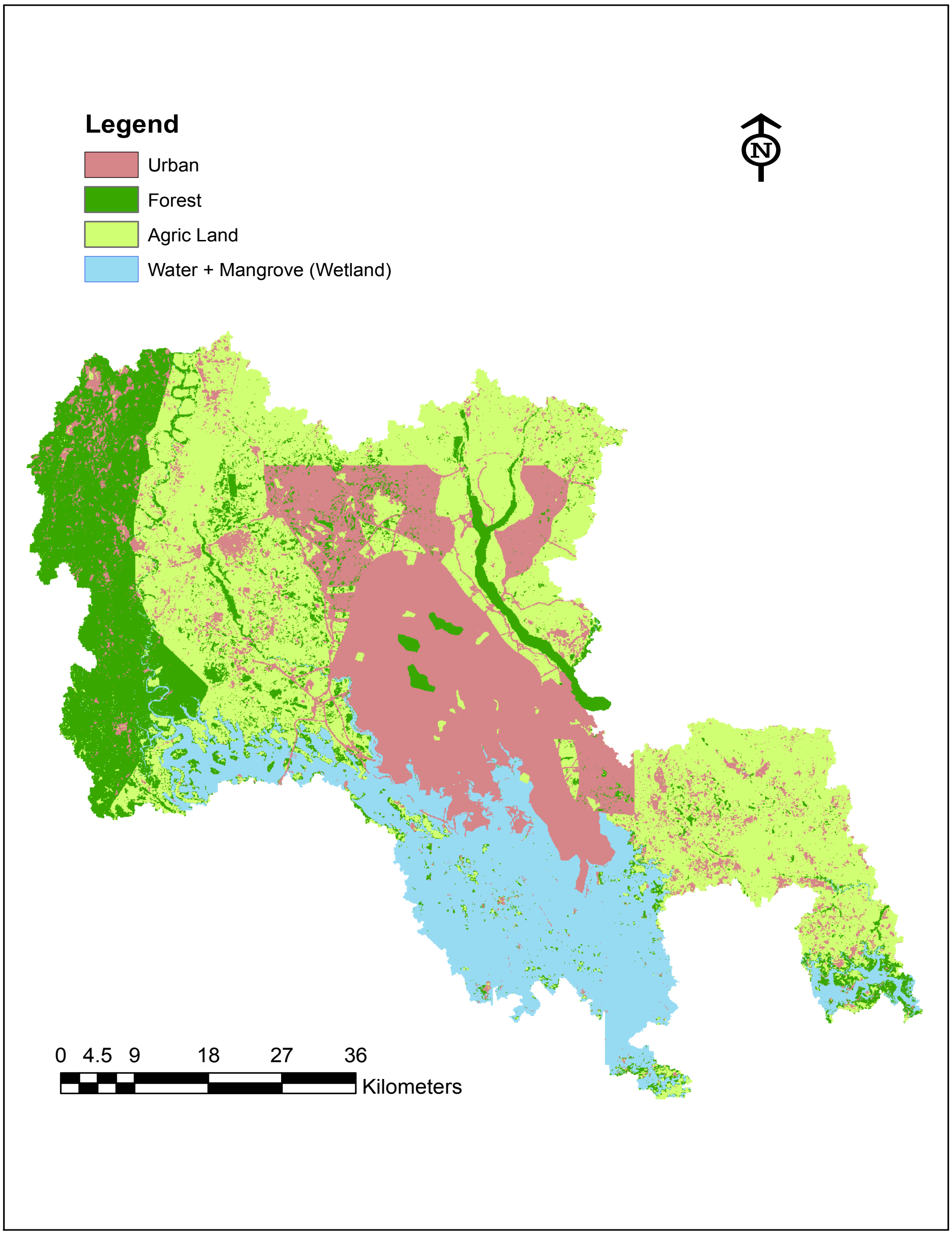
Appendix 6.2 UUMP future scenario map generated as input for hydrological modelling. The digitised Masterplan and urban sprawl classes were overlaid on the 2003 baseline map. Mangrove and water are classed as water for hydrological modelling due to their hydrologic properties.



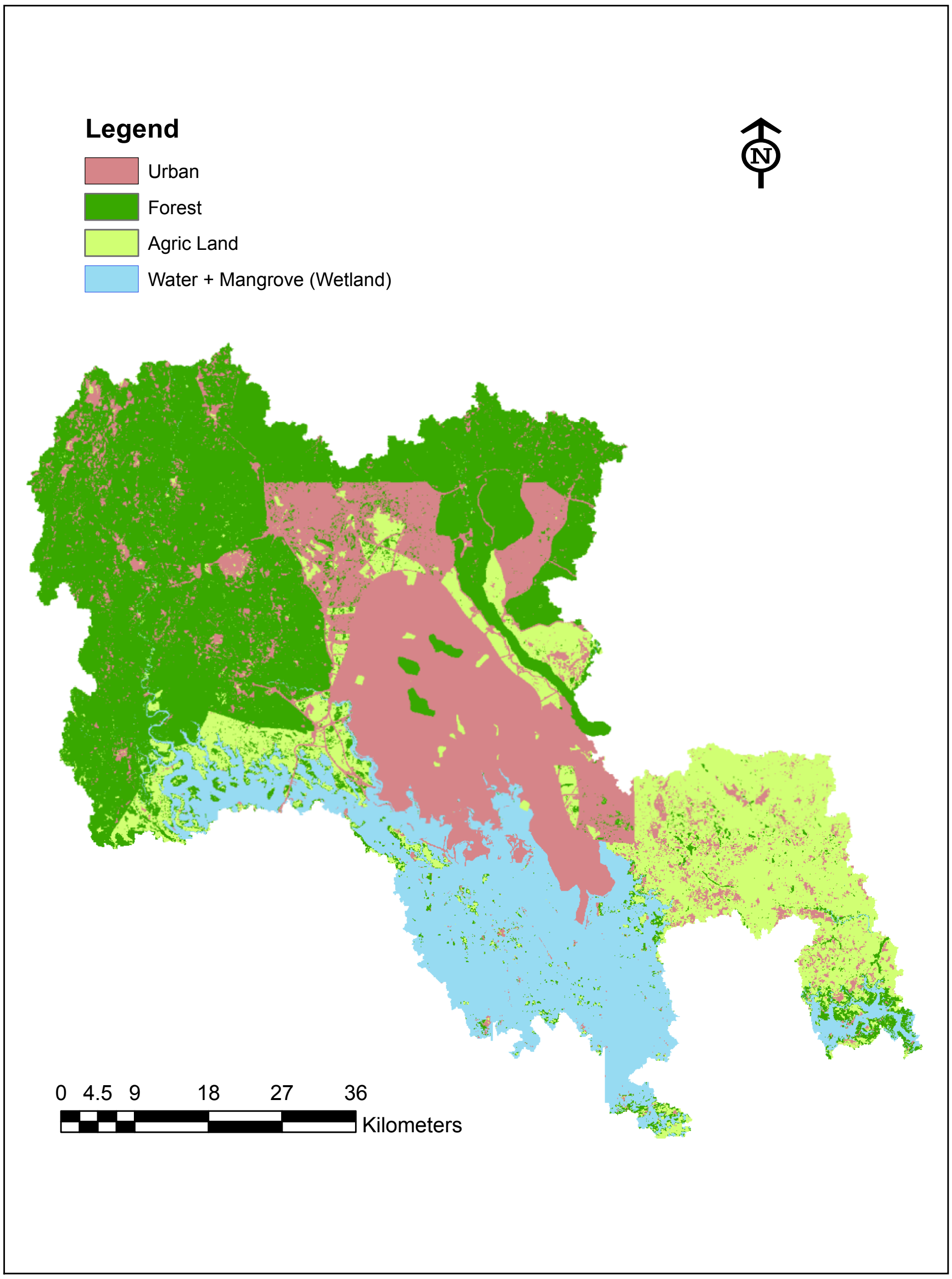
Appendix 6.3 Map of the No forest scenario generated as input for hydrological modelling. The digitised Masterplan map was overlaid on the 2003 baseline map. Forest class was eliminated. Mangrove and water are classed as water for hydrological modelling due to their hydrologic properties.



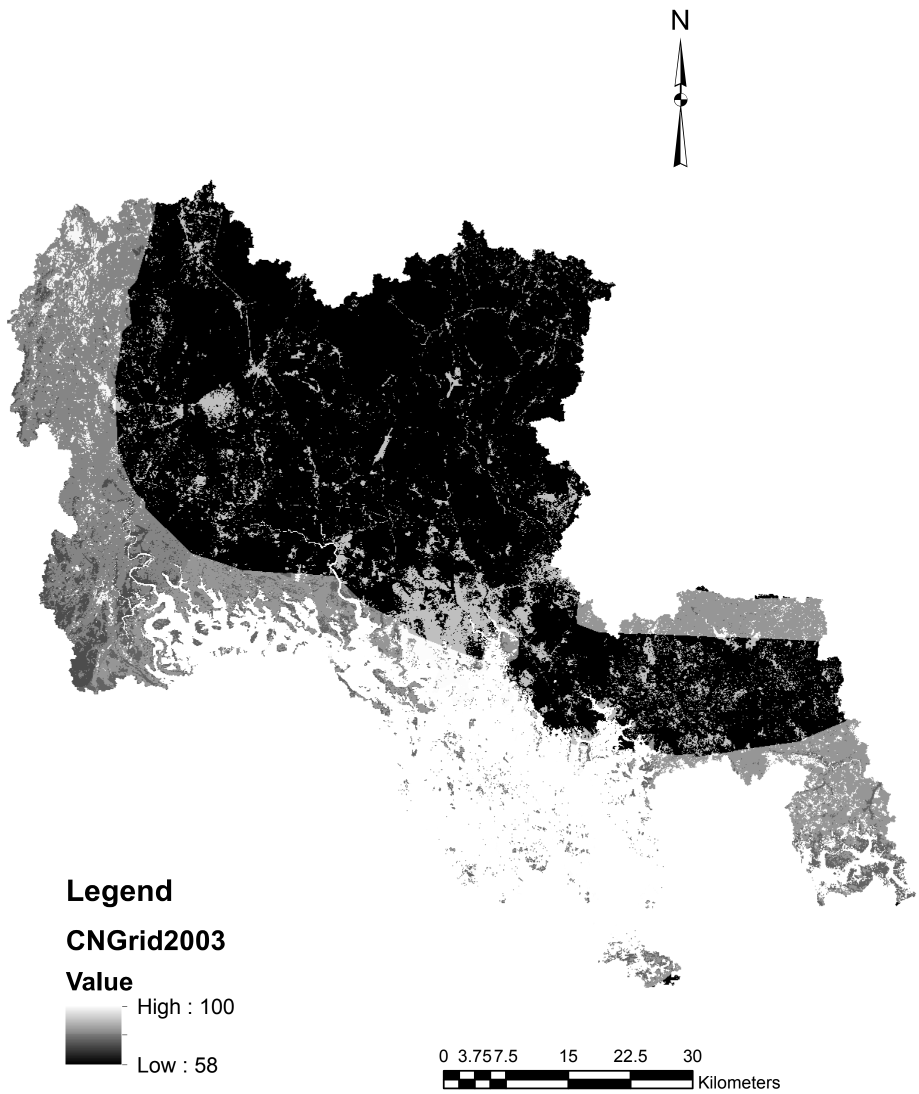
Appendix 6.4 Map of Low afforestation scenario generated was input for hydrological modelling. The digitised Masterplan map was overlaid on the 2003 baseline map. Forest classes was hypothetically generated Mangrove and water are classed as water for hydrological modelling due to their hydrologic properties. Future forest was increased to about 20%.



Appendix 6.5 Map of High afforestation scenario generated was input for hydrological modelling. The digitised Masterplan map was overlaid on the 2003 baseline map. Forest classes was hypothetically generated Mangrove and water are classed as water for hydrological modelling due to their hydrologic properties. Future forest was increased to about 40%.



Appendix 6.5b Example of Curve (CN) Grid map processed as input for hydrologic modelling. High CN means high runoff potential. While Low CN means low runoff potential.



Appendix 6.6 Percentage impervious values used as model input. UMP means Urban Masterplan, UUMP means urban Masterplan +urban sprawl. NF means No forest, LAF means low afforestation and HAF means High afforestation scenario.

Subbasins	PctImp-1986	PctImp-1995	PctImp-2003	PctImp-UMP	PctImp-UUMP	PctImp-NF	PctImp-LAF	PctImp-HAF
AOW40	9.99	9.51	8.80	9.52	13.76	12.33	13.76	13.76
AOW50	11.46	9.96	11.46	9.96	15.27	13.71	15.27	15.27
AOW60	8.80	9.54	9.99	9.54	12.76	12.20	12.76	12.76
BUGW180	4.92	4.94	4.62	4.32	4.08	4.10	4.08	4.08
BUGW160	4.89	4.94	5.07	5.13	5.19	5.24	5.19	5.19
BUGW150	9.26	13.27	14.04	36.52	38.48	38.56	38.39	38.39
BUGW140	9.21	11.24	11.46	40.36	46.87	46.99	46.85	46.85
BUGW130	9.15	9.15	11.46	13.25	33.73	34.04	33.71	33.96
BUGW120	8.44	9.39	12.13	11.61	12.17	12.87	12.15	12.73
BUGW110	9.09	9.58	10.28	10.05	9.17	10.11	9.16	10.11
BUGW100	9.39	9.39	15.81	15.13	25.95	26.52	25.92	26.51
DEGW250	7.04	7.04	7.66	7.44	6.96	7.60	7.60	7.33
DEGW240	8.90	8.90	10.93	10.33	9.77	10.40	10.40	10.26
DEGW230	8.82	8.82	11.18	10.55	9.04	9.99	9.99	9.94
DEGW220	6.15	6.15	6.51	6.27	6.07	6.43	6.43	6.07
DEGW210	9.09	9.09	15.16	13.99	11.87	12.83	12.83	12.83
DEGW200	8.88	8.88	12.28	11.94	9.51	10.60	10.60	10.60
DEGW190	8.87	8.87	12.69	12.53	10.01	11.09	11.09	11.09
DEGW180	8.84	8.84	16.26	15.32	12.15	13.15	13.15	13.14
DEGW170	9.07	9.07	17.52	17.07	14.08	15.08	15.08	15.08
DEGW160	9.24	9.24	15.87	15.65	13.32	14.24	14.24	14.24
DEGW150	10.53	10.53	13.67	12.90	10.52	11.58	11.58	11.56
DEGW140	9.47	9.47	16.91	16.56	13.95	14.94	14.94	14.94
IMOW100	9.10	9.81	14.79	12.83	19.57	20.65	19.93	20.29
IMOW90	9.27	9.27	11.62	10.64	16.06	23.71	16.10	16.65
IMOW80	9.12	9.12	17.87	11.72	22.97	22.97	22.97	23.70
IMOW70	9.50	10.11	15.83	10.43	20.90	21.66	20.89	21.62
IMOW60	9.50	9.57	4.36	11.98	9.88	10.95	9.81	10.95
PHCW260	4.85	4.44	3.65	3.00	2.99	3.00	3.00	3.00
PHCW250	3.80	3.50	14.47	29.24	36.05	36.08	36.03	36.03
PHCW220	11.92	15.20	8.60	14.20	14.97	15.01	15.01	15.01
PHCW210	7.54	8.83	26.77	43.76	44.86	44.86	44.85	44.85
PHCW200	9.58	9.30	18.48	23.01	25.45	25.45	25.45	25.45
PHCW180	8.68	8.91	16.55	45.96	47.15	47.28	47.15	47.15
PHCW160	16.58	27.80	20.37	50.00	50.84	50.86	50.84	50.84
PHCW190	12.86	18.74	21.17	39.99	47.56	47.69	47.58	47.58
PHCW300	10.61	18.25	5.36	5.09	4.78	4.89	4.79	4.79
PHCW240	10.09	14.16	9.99	11.28	12.23	12.28	12.25	12.25
PHCW230	11.46	18.62	14.93	14.43	17.49	18.15	17.49	17.49

Appendix 6.7 Table comprising of Subbasin curve numbers generated from the combination of soil and land-use maps.

SUB BASINS	CN-1986	CN-1995	CN-2003	CN-UMP	CN-UUMP	CN-NF	CN-LAF	CN-HAF
AOW40	74.45	74.43	85.62	74.43	75.44	75.70	75.44	75.44
AOW50	70.78	69.92	70.78	69.92	71.33	72.01	71.33	71.33
AOW60	85.62	85.35	74.45	85.38	84.94	85.54	84.94	84.94
BUGW180	98.84	97.56	98.84	98.07	98.01	98.09	98.01	98.01
BUGW160	97.56	74.60	97.54	97.77	97.74	97.89	97.74	97.74
BUGW150	74.60	74.60	75.74	82.09	82.09	83.33	82.09	82.10
BUGW140	66.49	66.49	66.78	79.51	79.47	80.92	79.47	79.47
BUGW130	66.69	66.69	66.23	75.90	75.83	79.03	75.83	77.51
BUGW120	73.48	73.48	74.30	74.93	74.93	77.26	74.93	78.70
BUGW110	66.67	66.67	66.67	66.00	66.00	70.05	66.00	72.03
BUGW100	66.65	66.65	68.73	73.57	73.54	75.65	73.54	77.42
DEGW250	83.80	84.80	84.62	84.71	84.72	85.67	85.67	84.06
DEGW240	78.18	98.90	78.94	78.87	78.92	80.99	80.99	76.64
DEGW230	78.92	89.50	79.96	79.91	79.87	80.72	80.72	75.97
DEGW220	88.91	95.39	89.28	89.33	89.40	90.16	90.16	89.25
DEGW210	67.40	68.20	69.37	69.28	69.31	71.03	71.03	74.74
DEGW200	78.65	84.68	80.44	80.35	80.39	80.67	80.67	75.60
DEGW190	78.61	80.60	80.54	80.40	80.42	80.79	80.79	75.76
DEGW180	68.78	71.56	71.79	71.53	71.58	72.68	72.68	75.43
DEGW170	78.62	80.80	81.58	81.46	81.48	81.71	81.71	77.20
DEGW160	69.13	72.41	72.68	72.59	72.70	74.23	74.23	75.50
DEGW150	66.69	67.91	68.42	68.22	68.29	69.77	69.77	74.48
DEGW140	72.79	74.16	75.46	75.36	75.35	76.11	76.11	76.35
IMOW100	66.65	66.75	71.23	71.22	71.22	73.34	71.23	73.58
IMOW90	66.25	66.73	69.66	69.66	69.66	74.06	69.66	74.39
IMOW80	67.01	67.01	72.75	72.75	72.75	72.75	71.98	77.48
IMOW70	67.20	67.43	71.98	71.98	71.98	73.25	71.98	71.72
IMOW60	67.20	67.12	67.79	67.98	67.98	68.56	67.79	74.84
PHCW260	96.36	96.20	99.77	99.77	99.73	99.75	99.73	99.73
PHCW250	98.59	98.92	76.62	83.76	83.77	84.85	83.77	83.77
PHCW220	76.58	79.75	93.70	95.05	95.01	95.19	95.01	95.01
PHCW210	96.50	97.87	79.14	84.49	84.50	85.95	84.50	84.50
PHCW200	74.73	75.03	86.52	88.78	88.72	89.46	88.72	88.72
PHCW180	94.69	91.20	71.18	79.81	79.81	80.19	79.81	79.81
PHCW160	76.00	82.91	72.08	80.90	80.89	81.80	80.89	80.89
PHCW190	86.26	89.61	72.56	82.71	82.70	83.12	82.70	82.70
PHCW300	68.74	72.60	96.44	96.50	96.51	96.72	96.51	96.51
PHCW240	68.89	72.24	96.58	96.95	96.95	97.05	96.95	96.95
PHCW230	68.53	73.32	76.15	77.88	77.85	78.74	77.85	77.85
Average	76.73	78.21	78.28	80.25	80.30	81.40	80.59	81.13

Appendix 6.8 Modelled Peak flow data for the 1986, 1995 and 2003 event.AO=Andoni Ogoni; BUG Buguma Basin; DEG=Degema; PHC=Port-Harcourt Basins.

Subbasins	Area (km2)	Qp-1986	Qp-1995	Qp-2003
AO W40	178.849	101.4	115.2	191.1
AO W50	140.113	77.8	88.9	151.3
AO W60	209.569	179.2	217.6	327.6
BUG W180	76.872	92.7	112.6	154.2
BUG W160	178.2	206.8	253.4	347.8
BUG W150	121.5	71.8	100.9	148.6
BUG W140	151.76	66.6	80.9	126.8
BUG W130	187.56	80.4	78.6	137.2
BUG W120	344.67	163.5	147.5	264.2
BUG W110	73.133	32.7	37	61.3
BUG W100	116.7	51.8	54.5	110.8
DEG W250	144.82	128.2	163.8	245.8
DEG W240	131.27	103.1	183.9	208.8
DEG W230	45.453	36.9	57.4	74.6
DEG W220	86.413	92.5	123.6	165
DEG W210	76.077	35.5	41.4	79.7
DEG W200	46.197	39.7	57	80.6
DEG W190	75.306	57	75.1	119
DEG W180	61.547	33.4	45.4	81.7
DEG W170	139.34	94.8	121	204.4
DEG W160	23.334	15.7	22.7	37.5
DEG W150	94.704	45.8	56.9	104
DEG W140	247.15	125.9	136.3	257.3
IMO W100	237.27	97.7	86.8	161.3
IMO W90	21.734	12.8	17.3	29.6
IMO W80	94.285	42.8	46.9	86
IMO W70	201.66	93.7	107.3	186.8
IMO W60	91.179	41.6	45.2	83
PHC W160	111.71	51.4	69.1	107.1
PHC W180	114.87	55.9	76.6	123.7
PHC W190	88.415	49.3	76.8	123.8
PHC W200	31.052	31.9	42.5	58.2
PHC W210	114.84	67.8	105.9	138.9
PHC W220	81.673	94.7	110	159.5
PHC W230	203.95	100.4	92.4	168.6
PHC W240	188.94	202.6	254.1	343.9
PHC W250	90.991	58.5	81	113.6
PHC W260	14.076	17	20.6	28.2
PHC W300	183.8	203	245.5	345.1

Appendix 6.9 Estimated peak flow for U1 and U2. U1= 1986 LU +1986 storm and U2=2003 LU + 1986 storm condition AO=Andoni Ogoni; BUG Buguma Basin; DEG=Degema; PHC=Port-Harcourt Basins.

Subbasin Code	U1	U2	% Δ in Peak discharge within subbasins
AO W40	101.4	101	-0.39448
AO W50	77.8	74.3	-4.49871
AO W60	179.2	178.1	-0.61384
BUG W180	92.7	92.7	0
BUG W160	206.8	206.7	-0.04836
BUG W150	71.8	77.2	7.520891
BUG W140	66.6	68.5	2.852853
BUG W130	80.4	80.7	0.373134
BUG W120	163.5	171.3	4.770642
BUG W110	32.7	32.2	-1.52905
BUG W100	51.8	58.6	13.12741
DEG W250	93.8	131.8	40.51173
DEG W240	73.4	106.7	45.36785
DEG W230	26.4	38.5	45.83333
DEG W220	69.5	93.3	34.2446
DEG W210	24.1	40.4	67.63485
DEG W200	28.4	42.2	48.59155
DEG W190	40.7	62	52.33415
DEG W180	22.6	40	76.99115
DEG W170	67.8	109.5	61.50442
DEG W160	10.7	18.4	71.96262
DEG W150	30.9	50.6	63.75405
DEG W140	88.6	143.7	62.18962
IMO W100	97.7	102.2	4.605937
IMO W90	12.8	13.4	4.6875
IMO W80	42.8	44.7	4.439252
IMO W70	93.7	94.3	0.640342
IMO W60	41.6	43.5	4.567308
PHC W160	51.4	60.1	16.92607
PHC W180	55.9	64.1	14.66905
PHC W190	49.3	61.8	25.35497
PHC W200	31.9	32.4	1.567398
PHC W210	67.8	77.7	14.60177
PHC W220	94.7	92.9	-1.90074
PHC W230	100.4	107.9	7.47012
PHC W240	202.6	203.3	0.345508
PHC W250	58.5	59.3	1.367521
PHC W260	17	17	0
PHC W300	203	203.4	0.197044

Appendix 6.10 Result of Qp response to urbanization under six future urban and storm scenarios. AO=Andoni Ogoni; BUG Buguma Basin; DEG=Degema; PHC=Port-Harcourt Basins. UMP =Urban Masterplan; UUMP= Urban sprawl + Urban Masterplan; Qp= peak Discharge.

Subbasins	Qp-UMP(44yr)	Qp-UUMP(44yr)	Qp-UMP(57yr)	Qp-UUMP(57yr)	Qp-UMP(100yr)	Qp-UUMP(100yr)
AO W40	131	145.4	158.5	176.3	255.4	278.9
AO W50	118.2	134.7	144	163.8	235.2	260.8
AO W60	316.7	310.4	368.6	364.4	542.4	536.7
BUG W180	163.8	162.6	185.5	185.5	258	258
BUG W160	369.4	366.7	418.8	418.7	583.5	583.3
BUG W150	185.3	185	214.8	216	313.7	314.9
BUG W140	205.7	209.8	239.3	245.1	352.6	358.6
BUG W130	142.5	166.1	171.2	197.2	271.2	299.6
BUG W120	102.3	101.9	124.3	125.1	203.1	204
BUG W110	35.7	34.8	44.3	43.7	75.6	74.9
BUG W100	99.5	108.1	119.6	129.6	189.8	200.8
DEG W250	255	252.7	295.2	295.1	429.3	429.2
DEG W240	214	212.1	250.4	250.5	372.5	372.6
DEG W230	77.3	76.3	90.1	89.7	132.9	132.6
DEG W220	175.8	174.6	200.7	200.8	283.3	283.4
DEG W210	57.7	55.8	70.2	68.8	114.4	112.9
DEG W200	85.5	84.5	99	98.8	143.8	143.6
DEG W190	119.7	117.8	139.9	139.1	207.7	206.9
DEG W180	76.2	74.1	91	89.6	142	140.6
DEG W170	189.4	185.6	222	219.9	332.1	330.1
DEG W160	39.8	39.3	46.7	46.5	69.5	69.3
DEG W150	83	80.3	101	99.1	164.6	162.7
DEG W140	158	152.3	189.7	185.4	300.8	295.9
IMO W100	89.4	97.1	109.2	118.5	180.5	191.2
IMO W90	33	33.5	39.2	40	60.1	60.8
IMO W80	79.6	87.3	96.3	105.2	154.6	164.3
IMO W70	178.6	194.3	216.3	234.7	348.6	368.6
IMO W60	53	50.8	65.1	63.4	108.5	106.5
PHC W160	141.4	140.7	163.6	164.1	238.6	238.6
PHC W180	171.2	170.7	198.3	199.1	289.3	289.3
PHC W190	167.7	168.6	192.7	194.8	275.9	275.9
PHC W200	63.6	63.2	72.5	72.6	102.2	102.2
PHC W210	157.3	156.8	181.7	182.5	263.8	263.8
PHC W220	171.8	170.5	194.9	194.9	272	272
PHC W230	79.1	80.5	95	97.3	151.1	151.1
PHC W240	358.3	355.7	407.1	407.1	569.5	569.5
PHC W250	143	144.5	165.7	168.4	241.6	241.6
PHC W260	30	29.8	34	34	47.3	47.3
PHC W300	361.5	358.9	410.7	410.8	574.7	574.7

Appendix 6.11 Result of Peak flow response to afforestation under nine plausible afforestation and storm scenarios. PHC=Port-Harcourt Basins. UMP=Urban Masterplan; UUMP=Urban sprawl + Urban Masterplan; NF=No Forest; LAF=Low Afforestation; HAF=High Afforestation; Qp= peak Discharge.

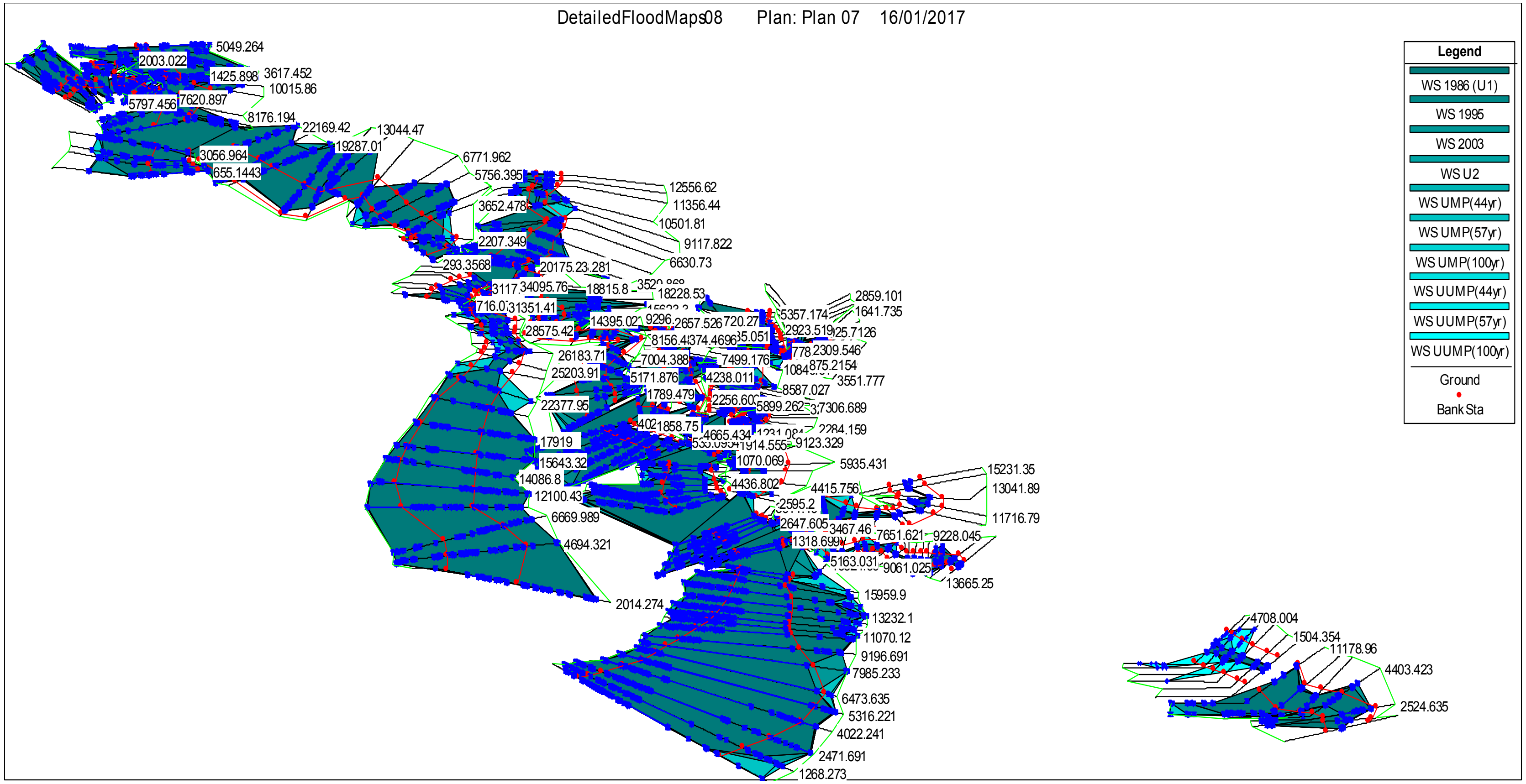
Subbasins	Qp-NF(44yr)	Qp-NF(57yr)	Qp-NF(1004yr)	Qp-LAF(44yr)	Qp-LAF(57yr)	Qp-LAF(1004yr)	Qp-HAF(44yr)	Qp-HAF(57yr)	Qp-HAF(1004yr)
AO W40	144.6	175.6	278.2	145.4	176.3	278.9	145.4	176.3	278.9
AO W50	135.4	164.8	262.2	134.7	163.8	260.8	134.7	163.8	260.8
AO W60	313.5	367.7	540.2	310.4	364.4	536.7	310.4	364.4	536.7
BUG W180	162.6	185.5	258	162.6	185.5	258	162.6	162.6	258
BUG W160	367.3	419.4	584.1	366.7	418.7	583.3	366.7	418.7	583.3
BUG W150	193.3	225.1	326.4	184.9	215.9	314.8	185	216	315
BUG W140	222	258.8	376.6	209.7	245.1	358.6	209.7	245.1	358.6
BUG W130	202.2	238.7	357.5	166	197.2	299.6	184.6	218.6	329.6
BUG W120	130.1	158.5	253.9	101.9	125.1	204	149.8	181.8	288.5
BUG W110	49	60.6	100	34.7	43.7	74.9	56.8	69.8	113.2
BUG W100	122.8	146.5	224.2	108	129.6	200.8	135.2	160.7	243.5
DEG W250	259.6	302.3	437.1	259.6	259.6	437.1	248	290.1	423.5
DEG W240	225.3	264.4	388.1	225.3	264.4	388.1	197.1	234.5	354
DEG W230	78.2	91.7	134.8	78.2	91.7	134.8	67.7	80.6	122.1
DEG W220	175.9	202.1	284.6	175.9	202.1	284.6	174.3	200.5	283.2
DEG W210	63.5	77.8	125.5	63.5	77.8	125.5	80.3	97	152.1
DEG W200	85.1	99.3	144.2	85.1	99.3	144.2	76.5	90.5	135
DEG W190	119.7	141.1	209.2	119.7	141.1	209.2	98.1	117.6	180.7
DEG W180	78.3	94.3	146.4	78.3	94.3	146.4	87.6	87.6	159
DEG W170	188.5	223	333.9	188.5	333.9	333.9	146.7	176.3	272.8

Subbasins	Qp-NF(44yr)	Qp-NF(57yr)	Qp-NF(1004yr)	Qp-LAF(44yr)	Qp-LAF(57yr)	Qp-LAF(1004yr)	Qp-HAF(44yr)	Qp-HAF(57yr)	Qp-HAF(1004yr)
DEG W160	40.6	47.8	70.7	40.6	47.8	70.7	41.5	48.7	71.6
DEG W150	89.1	109.2	176.4	89.1	109.2	176.4	115.3	138.9	215.7
DEG W140	163.7	198.5	314.4	163.7	198.5	314.4	166.9	202.3	319.9
IMO W100	117.8	142.9	227.3	97.6	119	191.8	119.7	145.2	230.9
IMO W90	37.6	44.2	65.2	33.5	40	60.8	37.4	44	65.2
IMO W80	91.7	110.4	172.1	85.9	103.6	162.3	114.2	135.8	206.1
IMO W70	210.1	252.7	393.1	194.3	234.7	368.6	227	273.2	425.1
IMO W60	54.5	67.7	112.8	50.4	63	106	86.2	104.7	165.7
PHC W160	147	171.1	248.6	140.7	164.1	239	140.7	164.1	239
PHC W180	173	201.7	293.4	170.7	199.1	290.1	170.7	170.7	290.1
PHC W190	169.6	195.9	279	168.6	194.8	277.7	168.6	194.8	277.7
PHC W200	63.5	72.9	102.6	63.2	72.6	102.2	63.2	72.6	102.2
PHC W210	167.7	194.7	280.7	156.8	182.5	264.6	156.8	182.5	264.6
PHC W220	170.7	195.1	272.2	170.5	194.9	272	170.5	194.9	272
PHC W230	88.3	106.5	166.9	80.5	97.3	153.6	80.5	97.3	153.6
PHC W240	357	408.4	571.2	355.7	407.1	569.5	355.7	407.1	569.5
PHC W250	149.9	174.3	251.6	144.5	144.5	244.3	144.5	168.4	244.3
PHC W260	29.8	34	47.3	29.8	34	47.3	29.8	34	47.3
PHC W300	360.8	412.8	577.2	358.9	410.8	574.8	358.9	410.8	574.8

Appendix 6.12 Modelled result of peak flow responses to the three Alternatives in four Basins. . AO=Andoni Ogoni; BUG Buguma Basin; DEG=Degema; PHC=Port-Harcourt Basins. UMP =Urban Masterplan; UUMP= Urban sprawl + Urban Masterplan; Qp= peak Discharge. QP-2003= 2003peak flow, Q-2003(Phase-1 DEV) Alternatives = the peakflow due to the Phase-1 alternative.

Alternative Location	Host Basin Code	Subbasin Code	Area (km^2)	Qp-2003 (m^3/s)	Qp-2003(Phase-1 Dev)Alternatives (m^3/s)	%Δ
Bori	AO	AOW60	209.569	327.6	326.4	-0.37
		AOW40	178.849	191.1	212.9	11.41
		AO W50	140.113	151.3	182.5	20.62
		AO Outlet	**528.531**	**650.2**	**710.8**	**9.32**
Current location	**BUG**					
		BUGW180	76.872	154.2	154.2	0.00
		BUGW160	178.2	347.8	347.8	0.00
		BUGW150	121.5	148.6	148.5	-0.07
		BUGW140	151.76	126.8	138.6	9.31
		BUGW130	187.56	137.2	137.2	0.00
		BUGW120	344.67	264.2	264.2	0.00
		BUGW110	73.133	61.3	61.3	0.00
		BUGW100	116.7	110.8	110.8	0.00
		BUG Outlet	**1250.395**	**840.6**	**853.2**	**1.50**
Omoku Area	DEG	DEGW250	144.82	245.8	245.9	0.04
		DEGW240	131.27	208.8	208.8	0.00
		DEGW230	45.453	74.6	74.6	0.00
		DEGW220	86.413	165	165.1	0.06
		DEGW210	76.077	79.7	79.8	0.13
		DEGW200	46.197	80.6	80.7	0.12
		DEGW190	75.306	119	118.9	-0.08
		DEGW180	61.547	81.7	81.7	0.00
		DEGW170	139.34	204.4	204.4	0.00
		DEGW160	23.334	37.5	37.6	0.27
		DEGW150	94.704	104	103.9	-0.10
		DEGW140	247.15	257.3	265.7	3.26
		DEG Outlet	**1171.611**	**1229.8**	**1238.5**	**0.71**
Current Location	PHC	PHCW160	111.71	107.1	108.5	1.31
		PHCW180	114.87	123.7	123.7	0.00
		PHCW190	88.415	123.8	123.8	0.00
		PHCW200	31.052	58.2	58.1	-0.17
		PHCW210	114.84	138.9	146.7	5.62
		PHCW220	81.673	159.5	159.5	0.00
		PHCW230	203.95	168.6	168.4	-0.12
		PHCW240	188.94	343.9	343.8	-0.03
		PHCW250	90.991	113.6	113.4	-0.18
		PHCW260	14.076	28.2	28.2	0.00
		PHCW300	183.8	345.1	345.1	0.00
		PHC Outlet	**1224.317**	**1476.8**	**1485.2**	**0.57**

Appendix 7.1 RAS output of selected rivers and profiles modelled for the GPH subbasin. WS Means water surface. U1 and U2 are urban scenarios, UMP means urban Masterplan. UUMP means Urban Masterplan + Urban Sprawl. Different shades of colours match the profiles. Keys can be viewed in the diagram.



Appendix 7.2 Modelled Waster Surface Elevation computed for 296 cross-sections and 10 Profiles. W.S means water surface elevation. UMP means Urban Masterplan, UUMP means urban Masterplan +urban sprawl. NF means No forest, LAF means low afforestation and HAF means High afforestation scenario.

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP5 7yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
		(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
T. Amadi Rch	2309.546	3.39	3.77	4.42	3.55	4.92	5.16	5.85	4.91	5.17	5.85
T. Amadi Rch	2057.07	3.29	3.66	4.28	3.44	4.76	5.01	5.71	4.76	5.02	5.71
T. Amadi Rch	1847.522	3.25	3.62	4.23	3.4	4.71	4.96	5.65	4.71	4.97	5.65
T. Amadi Rch	1678.48	3.24	3.6	4.22	3.39	4.69	4.94	5.63	4.69	4.95	5.63
T. Amadi Rch	1103.246	3.15	3.51	4.09	3.3	4.55	4.78	5.45	4.54	4.79	5.45
T. Amadi Rch	875.2154	2.96	3.3	3.85	3.09	4.28	4.5	5.15	4.27	4.51	5.15
T. Amadi Rch	595.8615	2.26	2.62	3.15	2.36	3.57	3.83	4.55	3.56	3.84	4.55
Soku Reach	34095.76	3.71	3.62	4.58	3.75	4.11	4.37	5.24	4	4.29	5.1
Soku Reach	33461.04	3.59	3.51	4.41	3.61	3.95	4.21	5.06	3.85	4.13	4.92
Soku Reach	32806.77	3.41	3.34	4.22	3.44	3.77	4.03	4.87	3.67	3.95	4.73
Soku Reach	32241.93	3.02	2.94	3.86	3.05	3.39	3.66	4.53	3.29	3.57	4.38
Soku Reach	31351.41	3.02	2.94	3.85	3.05	3.4	3.65	4.52	3.29	3.57	4.37
Soku Reach	30900.3	3.01	2.93	3.84	3.04	3.38	3.64	4.5	3.28	3.56	4.36
Soku Reach	30640.23	3	2.92	3.82	3.02	3.37	3.62	4.48	3.26	3.54	4.34
Soku Reach	29281.63	2.84	2.76	3.62	2.86	3.19	3.44	4.26	3.09	3.36	4.11
Soku Reach	28575.42	2.75	2.67	3.51	2.77	3.09	3.33	4.13	2.99	3.25	3.99
Soku Reach	28042.09	2.64	2.56	3.38	2.66	2.97	3.2	3.98	2.87	3.13	3.84
Soku Reach	27124.8	2.46	2.39	3.16	2.49	2.78	3	3.74	2.69	2.93	3.6
Soku Reach	26183.71	2.29	2.23	2.95	2.31	2.59	2.79	3.49	2.5	2.73	3.36
Soku Reach	25203.91	2.18	2.12	2.82	2.21	2.47	2.67	3.33	2.39	2.6	3.21

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Soku Reach	24016.2	2.08	2.02	2.68	2.1	2.35	2.53	3.17	2.27	2.47	3.05
Soku Reach	22377.95	1.9	1.85	2.46	1.92	2.15	2.32	2.9	2.08	2.27	2.8
Soku Reach	20393.28	1.78	1.73	2.31	1.8	2.02	2.19	2.72	1.95	2.13	2.63
Soku Reach	17919	1.73	1.67	2.25	1.74	1.96	2.12	2.64	1.89	2.07	2.56
Soku Reach	15643.32	1.7	1.65	2.22	1.72	1.93	2.1	2.61	1.87	2.04	2.53
Soku Reach	14086.8	1.68	1.63	2.2	1.7	1.92	2.08	2.59	1.85	2.03	2.51
Soku Reach	12100.43	1.67	1.62	2.19	1.69	1.91	2.07	2.58	1.84	2.01	2.49
Soku Reach	10021.08	1.66	1.61	2.18	1.68	1.89	2.05	2.56	1.83	2	2.48
Soku Reach	6669.989	1.58	1.53	2.09	1.6	1.81	1.97	2.46	1.75	1.92	2.38
Soku Reach	4694.321	1.44	1.4	1.91	1.46	1.65	1.8	2.26	1.59	1.75	2.18
Soku Reach	2014.274	1.03	0.99	1.42	1.04	1.21	1.33	1.71	1.16	1.29	1.65
Sambreiro Rch	9123.329	5.15	5.27	5.57	5.14	5.64	5.76	6.1	5.63	5.76	6.1
Sambreiro Rch	8142.11	4.52	4.57	4.71	4.52	4.74	4.8	4.98	4.74	4.8	4.98
Sambreiro Rch	7668.151	2.87	3.04	3.48	2.86	3.66	3.87	4.48	3.65	3.88	4.48
Sambreiro Rch	7055.343	2.86	3.03	3.47	2.85	3.65	3.87	4.47	3.65	3.87	4.47
Sambreiro Rch	5935.431	2.84	3.01	3.44	2.83	3.63	3.84	4.45	3.62	3.84	4.45
Sambreiro Rch	5450.645	2.76	2.93	3.36	2.75	3.56	3.77	4.39	3.55	3.78	4.39
Sambreiro Rch	4415.756	2.2	2.42	2.89	2.22	3.19	3.44	4.12	3.18	3.45	4.12
Sambreiro Rch	3227.193	1.88	2.18	2.65	1.95	3.02	3.29	3.98	3.02	3.3	3.98
Sambreiro Rch	2595.2	1.7	2.06	2.54	1.81	2.95	3.22	3.92	2.95	3.24	3.92
S.Eleme Rch	15231.35	2.14	2.39	2.81	2.18	3.11	3.36	4.03	3.11	3.37	4.03
S.Eleme Rch	14635.09	2.13	2.39	2.8	2.18	3.11	3.36	4.03	3.11	3.37	4.03
S.Eleme Rch	13041.89	1.83	2.15	2.62	1.92	2.99	3.26	3.95	2.99	3.28	3.95
S.Eleme Rch	11716.79	1.85	2.16	2.63	1.93	3	3.26	3.96	3	3.28	3.96
S.Eleme Rch	10548.3	1.84	2.15	2.62	1.92	2.99	3.26	3.95	2.99	3.28	3.95

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
S.Eleme Rch	9228.045	1.73	2.07	2.55	1.83	2.94	3.21	3.91	2.94	3.23	3.91
S.Eleme Rch	8835.141	1.69	2.04	2.53	1.8	2.93	3.2	3.9	2.93	3.22	3.9
S.Eleme Rch	7651.621	1.69	2.04	2.52	1.8	2.93	3.2	3.9	2.93	3.22	3.9
S.Eleme Rch	6509.708	1.69	2.04	2.52	1.8	2.92	3.2	3.9	2.93	3.21	3.9
S.Eleme Rch	5793.06	1.68	2.04	2.52	1.8	2.92	3.2	3.89	2.93	3.21	3.89
S.Eleme Rch	4682.95	1.68	2.03	2.52	1.79	2.92	3.2	3.89	2.93	3.21	3.89
S.Eleme Rch	3806.595	1.68	2.03	2.52	1.79	2.92	3.2	3.89	2.92	3.21	3.89
S.Eleme Rch	3467.46	1.68	2.03	2.52	1.79	2.92	3.2	3.89	2.92	3.21	3.89
S.Eleme Rch	3018.646	1.68	2.03	2.52	1.79	2.92	3.2	3.89	2.92	3.21	3.89
S.Eleme Rch	2648.755	1.68	2.03	2.52	1.79	2.92	3.2	3.89	2.92	3.21	3.89
S.Eleme Rch	2288.26	1.68	2.03	2.52	1.79	2.92	3.2	3.89	2.92	3.21	3.89
S.Eleme Rch	2050.328	1.68	2.03	2.52	1.79	2.92	3.2	3.89	2.92	3.21	3.89
Rumumasi Reach	5357.174	4.72	4.82	5	4.77	5.13	5.21	5.55	5.13	5.21	5.55
Rumumasi Reach	4997.979	4.72	4.81	4.98	4.76	5.11	5.18	5.51	5.1	5.18	5.51
Rumumasi Reach	4579.672	4.72	4.81	4.98	4.76	5.11	5.18	5.51	5.1	5.18	5.51
Rumumasi Reach	3195.744	4.56	4.62	4.74	4.59	4.83	4.88	5.38	4.83	4.89	5.38
Rumumasi Reach	2923.519	4.33	4.46	4.7	4.4	4.86	4.99	5.43	4.86	4.99	5.43
Rumumasi Reach	2584.753	4.32	4.46	4.69	4.39	4.86	4.98	5.42	4.86	4.98	5.42
Rumumasi Reach	2217.213	3.96	4.06	4.22	4.01	4.35	4.63	5.23	4.34	4.63	5.23
Rumumasi Reach	1878.588	2.94	3.26	3.77	3.08	4.15	4.37	4.99	4.14	4.38	4.99
Rumumasi Reach	1630.329	2.86	3.19	3.7	3.01	4.08	4.31	4.94	4.08	4.32	4.94
Rumumasi Reach	778.4335	2.57	2.91	3.44	2.7	3.84	4.09	4.76	3.84	4.1	4.76
Rumumasi Reach	473.6282	2.29	2.65	3.18	2.39	3.6	3.86	4.6	3.59	3.87	4.6
PhC Trib Rch	4665.434	2.15	2.48	2.94	2.22	3.25	3.51	4.18	3.25	3.52	4.18
PhC Trib Rch	4482.177	2.15	2.47	2.94	2.22	3.25	3.5	4.18	3.25	3.52	4.18

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
PhC Trib Rch	4233.093	2.15	2.47	2.94	2.22	3.25	3.5	4.18	3.25	3.52	4.18
PhC Trib Rch	3941.49	2.15	2.47	2.93	2.22	3.25	3.5	4.18	3.25	3.52	4.18
PhC Trib Rch2	2557.172	2.11	2.43	2.89	2.18	3.22	3.47	4.15	3.22	3.48	4.15
PhC Trib Rch2	2219.451	2.07	2.39	2.85	2.15	3.19	3.45	4.13	3.19	3.46	4.13
PhC Trib Rch2	1858.75	2.04	2.36	2.82	2.12	3.18	3.43	4.11	3.18	3.45	4.11
PhC Trib Rch2	1203.888	2	2.32	2.78	2.08	3.15	3.41	4.09	3.15	3.42	4.09
PhC River 3 Rch	3911.49	1.67	2.03	2.51	1.79	2.92	3.19	3.89	2.92	3.21	3.89
PhC River 3 Rch	3500.946	1.67	2.02	2.51	1.78	2.91	3.19	3.88	2.91	3.2	3.88
PhC River 3 Rch	3118.827	1.67	2.02	2.51	1.78	2.91	3.18	3.88	2.91	3.2	3.88
PhC River 3 Rch	2647.605	1.66	2.02	2.5	1.78	2.9	3.18	3.88	2.91	3.19	3.88
PhC Rv3 Rch	1318.699	1.65	2	2.49	1.76	2.89	3.16	3.86	2.89	3.18	3.86
PhC Rv3 Rch	1104.487	1.65	2	2.48	1.76	2.88	3.16	3.86	2.88	3.17	3.86
PhC Rv3 Rch	794.874	1.64	1.99	2.48	1.75	2.87	3.15	3.85	2.88	3.17	3.85
PhC River 2 Rch	5693.304	1.74	2.1	2.59	1.86	3	3.27	3.97	3	3.29	3.97
PhC River 2 Rch	5257.414	1.73	2.09	2.58	1.85	2.99	3.26	3.96	2.99	3.28	3.96
PhC River 2 Rch	4436.802	1.72	2.08	2.57	1.84	2.98	3.25	3.95	2.98	3.26	3.95
PhC River 2 Rch	3818.894	1.71	2.07	2.55	1.83	2.96	3.23	3.93	2.96	3.25	3.93
PhC River 2 Rch	3163.156	1.7	2.06	2.55	1.82	2.95	3.23	3.92	2.95	3.24	3.92
PhC River 2 Rch	2565.354	1.7	2.05	2.54	1.81	2.95	3.22	3.92	2.95	3.24	3.92
PhC River 2 Rch	2017.433	1.7	2.05	2.54	1.81	2.94	3.22	3.91	2.94	3.23	3.91
PhC River 1 Rch	10846.61	2.3	2.65	3.17	2.4	3.58	3.84	4.55	3.57	3.85	4.55
PhC River 1 Rch	10244.22	2.28	2.63	3.14	2.37	3.54	3.8	4.51	3.54	3.81	4.51
PhC River 1 Rch	9710.716	2.26	2.61	3.12	2.35	3.51	3.77	4.47	3.5	3.78	4.47
PhC River 1 Rch	8587.027	2.25	2.59	3.1	2.34	3.48	3.74	4.44	3.48	3.75	4.44
PhC River 1 Rch	7690.577	2.24	2.58	3.08	2.32	3.45	3.71	4.41	3.45	3.72	4.41

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
PhC River 1 Rch	7306.689	2.21	2.55	3.04	2.29	3.4	3.65	4.34	3.39	3.66	4.34
PhC River 1 Rch	6776.999	2.21	2.54	3.03	2.29	3.38	3.64	4.33	3.38	3.65	4.33
PhC River 1 Rch	6264.194	2.21	2.54	3.02	2.28	3.38	3.63	4.32	3.37	3.64	4.32
PhC River 1 Rch	5899.262	2.2	2.54	3.02	2.28	3.37	3.63	4.32	3.37	3.64	4.32
PhC River 1 Rch	5461.963	2.2	2.53	3.02	2.28	3.37	3.63	4.31	3.37	3.64	4.31
PhC River 1 Rch	4882.684	2.19	2.52	3	2.27	3.34	3.6	4.28	3.34	3.61	4.28
PhC River 1 Rch	4447.399	2.15	2.47	2.93	2.22	3.24	3.49	4.16	3.24	3.5	4.16
PhC Rv1 rch2	1914.555	1.77	2.13	2.63	1.89	3.05	3.32	4.02	3.05	3.34	4.02
PhC Rv1 rch2	1414.925	1.77	2.13	2.62	1.89	3.04	3.31	4.01	3.04	3.33	4.01
PhC Rv1 rch2	1070.069	1.76	2.12	2.62	1.88	3.03	3.3	4	3.04	3.32	4
PhC Rv1 rch2	728.6349	1.76	2.12	2.61	1.88	3.03	3.3	4	3.03	3.32	4
Okrika Rch	13665.25	3.49	3.4	4.32	3.59	3.47	3.76	4.55	3.49	3.78	4.55
Okrika Rch	12794.63	3.48	3.39	4.31	3.58	3.47	3.75	4.53	3.48	3.78	4.53
Okrika Rch	12072.56	3.48	3.39	4.3	3.58	3.46	3.75	4.53	3.48	3.78	4.53
Okrika Rch	11764	3.48	3.39	4.3	3.58	3.46	3.75	4.53	3.48	3.78	4.53
Okrika Rch	11324.64	3.47	3.38	4.3	3.58	3.46	3.74	4.53	3.48	3.77	4.53
Okrika Rch	10998.09	3.47	3.38	4.3	3.58	3.46	3.74	4.53	3.48	3.77	4.53
Okrika Rch	10578.72	3.32	3.24	4.11	3.42	3.37	3.65	4.41	3.38	3.68	4.41
Okrika Rch	10243.39	3.39	3.3	4.19	3.48	3.41	3.69	4.46	3.42	3.72	4.46
Okrika Rch	9061.025	3.26	3.19	4.04	3.36	3.34	3.61	4.37	3.35	3.64	4.37
Okrika Rch	8374.236	3.02	2.96	3.77	3.12	3.22	3.49	4.22	3.23	3.52	4.22
Okrika Rch	7687.396	2.72	2.68	3.47	2.8	3.09	3.37	4.1	3.1	3.39	4.1
Okrika Rch	7072.159	2.69	2.66	3.43	2.77	3.08	3.36	4.09	3.09	3.38	4.09
Okrika Rch	6655.038	2.65	2.63	3.39	2.74	3.07	3.34	4.07	3.08	3.37	4.07
Okrika Rch	5649.987	2.61	2.59	3.34	2.69	3.05	3.33	4.05	3.06	3.35	4.05

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Okrika Rch	5163.031	2.49	2.49	3.21	2.57	3.02	3.29	4.01	3.02	3.31	4.01
Okrika Rch	4237.385	2.45	2.45	3.13	2.52	2.99	3.27	3.99	3	3.29	3.99
Okrika Rch	3678.697	2.26	2.3	2.92	2.34	2.95	3.22	3.93	2.95	3.24	3.93
Okrika Rch	3059.927	1.75	2.05	2.56	1.86	2.89	3.17	3.87	2.9	3.19	3.87
Okrika Rch	2781.317	1.7	2.03	2.53	1.81	2.89	3.17	3.87	2.89	3.18	3.87
Okrika Rch	2379.053	1.67	2.01	2.5	1.78	2.89	3.16	3.87	2.89	3.18	3.87
Okrika Rch	2095.073	1.66	2.01	2.5	1.77	2.89	3.16	3.86	2.89	3.18	3.86
Odual Tributary	2003.022	9.18	9.72	9.87	9.21	9.9	10.1	10.65	9.89	10.1	10.65
Odual Tributary	1487.593	9.18	9.71	9.86	9.21	9.89	10.09	10.64	9.88	10.09	10.64
Odual Tributary	909.9347	9.18	9.71	9.86	9.2	9.88	10.08	10.64	9.88	10.08	10.64
N.Eleme Rch	3551.777	9.08	9.39	9.64	9.28	9.83	9.92	10.19	9.83	9.93	10.19
N.Eleme Rch	3102.823	7.86	8.1	8.29	8.04	8.43	8.51	8.73	8.44	8.51	8.73
N.Eleme Rch	2605.724	6.09	6.24	6.43	6.16	6.58	6.65	6.87	6.58	6.66	6.87
N.Eleme Rch	1887.28	3.51	3.92	4.56	3.69	5.05	5.29	5.97	5.05	5.3	5.97
N.Eleme Rch	1361.515	3.5	3.9	4.55	3.67	5.04	5.28	5.95	5.04	5.29	5.95
N.Eleme Rch	1063.356	3.5	3.9	4.54	3.66	5.03	5.27	5.94	5.03	5.28	5.94
N.Eleme Rch	624.9445	3.47	3.86	4.51	3.63	5.01	5.25	5.93	5.01	5.26	5.93
Lwr Choba Rch	3117.347	0.67	0.78	0.93	0.69	1.03	1.1	1.32	1.03	1.11	1.32
Lwr Choba Rch	2630.421	0.6	0.71	0.84	0.62	0.94	1	1.19	0.94	1	1.2
Lwr Choba Rch	2210.917	0.52	0.6	0.72	0.53	0.8	0.86	1.02	0.8	0.86	1.02
Lwr Choba Rch	1505.881	0.42	0.49	0.59	0.43	0.65	0.7	0.84	0.65	0.7	0.84
Lwr Choba Rch	1177.626	0.38	0.45	0.54	0.39	0.6	0.64	0.77	0.6	0.64	0.77
Lwr Choba Rch	716.0721	0.09	0.11	0.14	0.09	0.16	0.18	0.23	0.16	0.18	0.23
Lw Eagle Isl Rch	4028.788	1.97	2.29	2.75	2.05	3.12	3.39	4.07	3.12	3.4	4.07
Lw Eagle Isl Rch	3553.737	1.96	2.28	2.74	2.04	3.12	3.38	4.07	3.12	3.39	4.07

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP5 7yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Lw Eagle Isl Rch	2981.277	1.95	2.27	2.74	2.04	3.12	3.38	4.06	3.12	3.39	4.06
Lw Eagle Isl Rch	2431.181	1.94	2.27	2.73	2.03	3.11	3.37	4.06	3.11	3.39	4.06
Lw Eagle Isl Rch	1818.94	1.94	2.26	2.73	2.03	3.11	3.37	4.06	3.11	3.39	4.06
Lw Eagle Isl Rch	1129.461	1.9	2.24	2.71	2	3.1	3.36	4.05	3.1	3.38	4.05
Lw Eagle Isl Rch	535.0954	1.82	2.17	2.66	1.93	3.07	3.34	4.03	3.07	3.35	4.03
Kor Rive Rch	4708.004	12.03	12.16	12.72	11.98	12.47	12.66	13.24	12.6	12.8	15.65
Kor Rive Rch	4163.468	11.99	12.12	12.66	11.95	12.42	12.61	13.16	12.54	12.74	15.47
Kor Rive Rch	3440.388	11.69	11.81	12.33	11.64	12.1	12.29	12.8	12.22	12.41	15.14
Kor Rive Rch	2678.573	11.12	11.24	11.79	11.08	11.54	11.74	12.26	11.67	11.87	14.8
Kor Rive Rch	1504.354	10.13	10.22	10.7	10.09	10.49	10.66	11.14	10.6	10.77	13.49
Kor Rive Rch	749.9553	8.37	8.41	8.58	8.35	8.5	8.57	8.75	8.54	8.61	9.66
Iwofe Rch	2657.526	2.37	2.43	2.48	2.39	2.5	2.52	2.6	2.5	2.53	2.6
Iwofe Rch	2405.32	2.98	3.44	3.81	3.11	4.02	4.24	4.87	4.02	4.25	4.87
Iwofe Rch	1987.4	2.78	3.22	3.61	2.89	3.84	4.07	4.71	3.83	4.07	4.71
Iwofe Rch	1368.51	2.73	3.17	3.56	2.84	3.79	4.02	4.67	3.79	4.03	4.67
Iwofe Rch	644.0602	2.72	3.15	3.55	2.83	3.78	4.01	4.66	3.77	4.02	4.66
Iwofe Rch	374.4696	2.71	3.14	3.53	2.82	3.76	3.99	4.64	3.76	4	4.64
PhC Habour	11720.27	3.48	3.55	3.59	3.5	3.61	3.64	3.72	3.61	3.64	3.72
PhC Habour	11368.09	2.73	3.17	3.58	2.85	3.81	4.04	4.7	3.81	4.05	4.7
PhC Habour	10421.94	2.7	3.13	3.54	2.81	3.77	4	4.66	3.77	4.01	4.66
PhC Habour	9685.051	2.7	3.13	3.53	2.81	3.77	4	4.65	3.76	4.01	4.65
PhC Habour	9272.59	2.7	3.13	3.53	2.8	3.76	4	4.65	3.76	4.01	4.65
PhC Habour	8810.765	2.7	3.13	3.53	2.8	3.76	3.99	4.65	3.76	4	4.65
Isaka Lower Rch	7499.176	2.67	3.09	3.49	2.77	3.72	3.96	4.61	3.72	3.97	4.61
Isaka Lower Rch	7137.471	2.54	2.95	3.38	2.64	3.63	3.86	4.53	3.62	3.87	4.53

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP5 7yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Isaka Lower Rch	6491.283	2.49	2.91	3.34	2.59	3.6	3.84	4.51	3.59	3.85	4.51
Isaka Lower Rch	5762	2.49	2.9	3.33	2.58	3.59	3.83	4.51	3.58	3.84	4.51
Isaka Lower Rch	5223.925	2.49	2.9	3.33	2.58	3.59	3.83	4.51	3.58	3.84	4.51
Isaka Lower Rch	4238.011	2.48	2.89	3.33	2.57	3.58	3.83	4.5	3.58	3.84	4.5
Isaka Lower Rch	3629.504	2.45	2.85	3.29	2.54	3.55	3.79	4.47	3.54	3.8	4.47
Isaka Lower Rch	2256.603	2.35	2.72	3.17	2.42	3.43	3.68	4.35	3.43	3.69	4.35
Isaka Lower Rch	1248.921	2.32	2.67	3.12	2.38	3.39	3.63	4.3	3.39	3.64	4.3
Elelenwo Reach	2859.101	4.58	4.75	5.09	4.67	5.47	5.68	6.31	5.47	5.69	6.31
Elelenwo Reach	2569.424	4.57	4.73	5.07	4.66	5.44	5.65	6.28	5.44	5.66	6.28
Elelenwo Reach	2247.295	4.54	4.69	4.99	4.62	5.34	5.54	6.17	5.34	5.55	6.17
Elelenwo Reach	1641.735	3.73	3.91	4.57	3.75	5.06	5.3	5.98	5.05	5.31	5.98
Elelenwo Reach	1239.382	3.58	3.94	4.56	3.73	5.04	5.29	5.96	5.04	5.29	5.96
Elelenwo Reach	925.7126	3.57	3.92	4.55	3.71	5.03	5.28	5.95	5.03	5.28	5.95
Egbema Upper Rch	7620.897	10.19	10.05	10.54	9.66	10.18	10.46	11.29	10.15	10.45	11.27
Egbema Upper Rch	6975.507	10.18	10.04	10.53	9.66	10.17	10.45	11.27	10.15	10.44	11.26
Egbema Upper Rch	6615.183	10.17	10.04	10.52	9.66	10.17	10.45	11.26	10.14	10.44	11.25
Egbema Upper Rch	6056.989	10.15	10.03	10.5	9.64	10.16	10.44	11.23	10.13	10.42	11.22
Egbema Upper Rch	5797.456	10.12	10.02	10.48	9.63	10.15	10.42	11.21	10.12	10.41	11.2
Egbema Upper Rch	5091.818	10.02	9.98	10.4	9.58	10.11	10.38	11.13	10.09	10.36	11.12
Egbema Upper Rch	4798.4	10	9.97	10.38	9.57	10.11	10.37	11.11	10.08	10.36	11.1
Egbema Upper Rch	4247.958	9.91	9.93	10.32	9.53	10.07	10.33	11.05	10.05	10.32	11.04
Egbema Upper Rch	3888.238	9.6	9.83	10.11	9.38	9.99	10.22	10.86	9.97	10.21	10.86
Egbema Lower Rch	3066.631	9.15	9.67	9.81	9.18	9.83	10.03	10.56	9.83	10.03	10.56
Egbema Lower Rch	2515.038	9.06	9.51	9.63	9.08	9.65	9.82	10.3	9.64	9.82	10.3
Egbema Lower Rch	2087.512	6.57	7.16	7.3	6.6	7.34	7.51	8	7.32	7.51	8

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP5 7yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Egbema Lower Rch	1587.756	6.32	6.86	6.99	6.35	7.04	7.2	7.68	7.01	7.2	7.68
Egbema Lower Rch	1011.06	6.16	6.67	6.79	6.19	6.84	6.99	7.44	6.8	6.99	7.44
Egbema Lower Rch	600.1398	5.93	6.38	6.48	5.95	6.54	6.67	7.07	6.5	6.67	7.07
Egbema Lower Rch	219.8786	4.21	4.38	4.42	4.22	4.42	4.49	4.66	4.42	4.49	4.66
Eagle Isl Rch	20175.23	3.49	3.81	4.3	3.5	4.44	4.68	5.36	4.43	4.69	5.36
Eagle Isl Rch	19541.11	3.48	3.8	4.29	3.49	4.42	4.67	5.35	4.41	4.67	5.35
Eagle Isl Rch	18815.8	3.47	3.79	4.28	3.48	4.41	4.66	5.34	4.4	4.66	5.34
Eagle Isl Rch	18228.53	3.46	3.79	4.27	3.48	4.41	4.65	5.33	4.4	4.66	5.33
Eagle Isl Rch	17633.08	3.44	3.77	4.25	3.46	4.38	4.63	5.3	4.37	4.63	5.3
Eagle Isl Rch	17011.49	3.4	3.72	4.21	3.41	4.34	4.59	5.26	4.33	4.59	5.26
Eagle Isl Rch	15623.3	3.29	3.62	4.1	3.31	4.25	4.5	5.19	4.24	4.51	5.19
Eagle Isl Rch	15122.23	3.18	3.51	4.01	3.2	4.17	4.43	5.13	4.16	4.43	5.13
Eagle Isl Rch	14395.02	3.12	3.45	3.94	3.14	4.11	4.37	5.07	4.1	4.37	5.07
Eagle Isl Rch	13377.85	3.04	3.36	3.85	3.06	4.02	4.28	4.98	4.01	4.28	4.98
Eagle Isl Rch	12545	2.95	3.27	3.75	2.98	3.93	4.19	4.89	3.93	4.19	4.89
Eagle Isl Rch	11194.69	2.73	3.04	3.51	2.76	3.72	3.97	4.66	3.72	3.98	4.66
Eagle Isl Rch	10397.37	2.66	2.97	3.44	2.69	3.66	3.91	4.61	3.65	3.92	4.61
Eagle Isl Rch	9679.32	2.61	2.92	3.38	2.64	3.62	3.87	4.56	3.61	3.87	4.56
Eagle Isl Rch	9296.871	2.59	2.9	3.36	2.62	3.6	3.85	4.54	3.59	3.86	4.54
Eagle Isl Rch	8156.481	2.48	2.79	3.25	2.52	3.5	3.75	4.43	3.5	3.76	4.43
Eagle Isl Rch	7004.388	2.26	2.57	3.01	2.32	3.31	3.56	4.24	3.31	3.57	4.24
Eagle Isl Rch	6301.9	2.23	2.53	2.98	2.29	3.29	3.54	4.22	3.29	3.55	4.22
Eagle Isl Rch	5171.876	2.17	2.48	2.93	2.23	3.25	3.5	4.18	3.25	3.52	4.18
Eagle Isl Rch	3607.002	2.1	2.42	2.87	2.17	3.21	3.47	4.15	3.21	3.48	4.15
Eagle Isl Rch	2524.504	2.07	2.38	2.84	2.14	3.19	3.44	4.13	3.19	3.46	4.13

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Eagle Isl Rch	1789.479	2.02	2.34	2.8	2.1	3.16	3.42	4.1	3.16	3.43	4.1
Eagle Isl Rch	612.6847	1.99	2.31	2.77	2.07	3.14	3.4	4.08	3.14	3.41	4.08
Dutch Isl Rch	3217.171	1.88	2.04	2.47	1.86	2.57	2.75	3.44	2.56	2.75	3.44
Dutch Isl Rch	2847.968	1.88	2.04	2.47	1.86	2.57	2.74	3.44	2.56	2.74	3.44
Dutch Isl Rch	2638.333	1.88	2.04	2.47	1.86	2.57	2.74	3.43	2.56	2.74	3.43
Dutch Isl Rch	2284.159	1.86	2.02	2.45	1.84	2.55	2.72	3.42	2.54	2.72	3.42
Dutch Isl Rch	1930.845	1.84	2	2.43	1.82	2.53	2.7	3.4	2.52	2.7	3.4
Dutch Isl Rch	1520.077	1.84	1.99	2.43	1.82	2.52	2.69	3.4	2.51	2.69	3.4
Dutch Isl Rch	1231.084	1.83	1.99	2.42	1.81	2.52	2.69	3.4	2.51	2.69	3.4
Dutch Isl Rch	923.5763	1.8	1.95	2.38	1.78	2.48	2.65	3.36	2.47	2.65	3.36
Degema Upper Rch	10015.86	4.11	4.05	4.53	3.88	4.41	4.58	5.08	4.4	4.58	5.07
Degema Upper Rch	9447.894	3.95	3.99	4.43	3.82	4.38	4.53	4.99	4.36	4.53	4.98
Degema Upper Rch	8176.194	3.79	3.94	4.33	3.76	4.34	4.48	4.88	4.33	4.48	4.88
Degema Upper Rch	7296.695	3.75	3.93	4.32	3.75	4.33	4.47	4.87	4.32	4.47	4.87
Degema Upper Rch	7110.268	3.75	3.92	4.31	3.75	4.33	4.47	4.86	4.32	4.47	4.86
Degema Upper Rch	5995.249	3.74	3.92	4.31	3.74	4.33	4.47	4.86	4.32	4.47	4.86
Degema Lower Rch	3056.964	1.38	1.53	1.9	1.43	1.64	1.82	2.3	1.62	1.8	2.29
Degema Lower Rch	1958.294	1.22	1.36	1.71	1.27	1.46	1.62	2.09	1.44	1.61	2.08
Degema Lower Rch	1459.966	1.11	1.24	1.57	1.16	1.34	1.49	1.93	1.32	1.48	1.92
Degema Lower Rch	655.1443	0.84	0.97	1.27	0.89	1.06	1.2	1.6	1.04	1.19	1.59
Choba Rch	12556.62	6.11	6.81	7.76	6.25	8.21	8.5	9.39	8.2	8.52	9.4
Choba Rch	11981.62	6.11	6.8	7.76	6.25	8.2	8.5	9.38	8.2	8.51	9.39
Choba Rch	11356.44	6.03	6.71	7.65	6.17	8.08	8.36	9.18	8.08	8.37	9.19
Choba Rch	10501.81	5.79	6.43	7.31	5.92	7.7	7.96	8.74	7.7	7.97	8.75
Choba Rch	9117.822	4.75	5.15	5.64	4.83	5.98	6.21	6.98	5.98	6.22	6.99

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Choba Rch	6630.73	3.87	4.03	4.68	3.91	4.61	4.83	5.37	4.61	4.83	5.25
Choba Rch	5315.833	3.76	3.87	4.62	3.79	4.5	4.74	5.31	4.49	4.74	5.17
Choba Rch	3529.868	3.73	3.83	4.6	3.77	4.46	4.7	5.28	4.45	4.71	5.14
Choba Rch	2739.644	3.73	3.82	4.6	3.76	4.45	4.7	5.27	4.44	4.7	5.13
Choba Rch	1148.281	3.73	3.82	4.6	3.76	4.44	4.69	5.27	4.43	4.69	5.12
Choba Rch	589.6992	3.73	3.82	4.6	3.76	4.44	4.69	5.27	4.43	4.69	5.12
Buguma Rch	22169.42	3.71	3.91	4.29	3.73	4.32	4.46	4.84	4.31	4.46	4.84
Buguma Rch	20077.09	3.71	3.91	4.29	3.73	4.32	4.46	4.83	4.31	4.46	4.83
Buguma Rch	19287.01	3.71	3.91	4.29	3.73	4.32	4.46	4.83	4.31	4.46	4.83
Buguma Rch	14320.91	3.57	3.74	4.08	3.58	4.11	4.24	4.59	4.11	4.24	4.58
Buguma Rch	13044.47	3.19	3.38	3.75	3.21	3.79	3.92	4.28	3.78	3.92	4.28
Buguma Rch	11091.03	2.58	2.81	3.3	2.61	3.33	3.46	3.83	3.32	3.46	3.83
Buguma Rch	8542.064	2.44	2.65	3.06	2.47	3.09	3.22	3.57	3.08	3.22	3.57
Buguma Rch	6771.962	2.35	2.55	2.87	2.37	2.9	3.02	3.36	2.89	3.02	3.36
Buguma Rch	5756.395	1.88	2.06	2.39	1.9	2.42	2.55	2.91	2.41	2.55	2.91
Buguma Rch	4494.115	1.57	1.75	2.1	1.59	2.14	2.28	2.68	2.13	2.28	2.68
Buguma Rch	3652.478	1.49	1.67	2.01	1.51	2.05	2.19	2.59	2.04	2.19	2.59
Buguma Rch	2207.349	1.34	1.5	1.81	1.36	1.84	1.97	2.35	1.84	1.97	2.35
Bugumlma Rch	1463.724	1.15	1.29	1.57	1.16	1.6	1.72	2.06	1.6	1.72	2.06
Buguma Rch	293.3568	0.81	0.93	1.18	0.82	1.21	1.32	1.63	1.2	1.32	1.63
Bori River Rch	11178.96	13.7	13.93	14.48	13.7	14.44	14.66	15.28	14.41	14.64	15.19
Bori River Rch	7423.903	13.7	13.92	14.47	13.69	14.42	14.64	15.26	14.4	14.63	15.17
Bori River Rch	5467.596	13.69	13.91	14.45	13.68	14.41	14.62	15.23	14.38	14.61	15.14
Bori River Rch	4403.423	13.64	13.85	14.36	13.64	14.32	14.52	15.08	14.29	14.5	15
Bori River Rch	2524.635	13.48	13.66	14.09	13.47	14.06	14.22	14.69	14.03	14.21	14.62

Reach	River Station	W.S. Elev 1986	W.S. Elev 1995	W.S. Elev 2003	W.S. Elev U2	W.S. Elev UMP 44yr	W.S. Elev UMP 57yr	W.S. Elev UMP 100yr	W.S. Elev UUMP 44yr	W.S. Elev UUMP 57yr	W.S. Elev UUMP 100yr
Bori River Rch	543.6863	9.31	9.43	9.72	9.3	9.69	9.8	10.14	9.68	9.8	10.09
Bonny River Rch	15959.9	1.62	1.97	2.46	1.73	2.85	3.13	3.83	2.86	3.15	3.83
Bonny River Rch	15252.99	1.61	1.96	2.45	1.72	2.85	3.12	3.82	2.85	3.14	3.82
Bonny River Rch	14245.93	1.6	1.95	2.44	1.71	2.83	3.11	3.81	2.84	3.13	3.81
Bonny River Rch	13232.1	1.59	1.94	2.43	1.7	2.83	3.1	3.8	2.83	3.12	3.8
Bonny River Rch	12346.08	1.58	1.93	2.42	1.69	2.82	3.1	3.79	2.82	3.11	3.79
Bonny River Rch	11616.86	1.57	1.92	2.41	1.69	2.81	3.09	3.79	2.81	3.11	3.79
Bonny River Rch	11070.12	1.57	1.92	2.41	1.68	2.81	3.09	3.79	2.81	3.1	3.79
Bonny River Rch	10425.34	1.57	1.92	2.4	1.68	2.81	3.08	3.78	2.81	3.1	3.78
Bonny River Rch	9196.691	1.56	1.91	2.4	1.67	2.8	3.08	3.78	2.8	3.1	3.78
Bonny River Rch	7985.233	1.56	1.91	2.4	1.67	2.8	3.08	3.78	2.8	3.1	3.78
Bonny River Rch	6473.635	1.56	1.91	2.4	1.67	2.8	3.08	3.78	2.8	3.09	3.78
Bonny River Rch	5316.221	1.56	1.91	2.4	1.67	2.8	3.08	3.78	2.8	3.09	3.78
Bonny River Rch	4022.241	1.56	1.91	2.4	1.67	2.8	3.08	3.77	2.8	3.09	3.77
Bonny River Rch	2471.691	1.56	1.91	2.39	1.67	2.8	3.07	3.77	2.8	3.09	3.77
Bonny River Rch	1268.273	1.55	1.9	2.39	1.66	2.79	3.07	3.77	2.79	3.09	3.77
Bonny River Rch	314.701	1.54	1.88	2.37	1.65	2.78	3.05	3.75	2.78	3.07	3.75
Abua Rch	5049.264	10.21	10.06	10.56	9.68	10.19	10.48	11.32	10.16	10.46	11.3
Abua Rch	4412.543	10.21	10.06	10.56	9.68	10.19	10.48	11.32	10.16	10.46	11.3
Abua Rch	3617.452	10.21	10.06	10.56	9.67	10.19	10.47	11.31	10.16	10.46	11.3
Abua Rch	2596.925	10.21	10.06	10.56	9.67	10.19	10.47	11.31	10.16	10.46	11.3
Abua Rch	1425.898	10.21	10.06	10.56	9.67	10.19	10.47	11.31	10.16	10.46	11.3
Abua Rch	887.2714	10.21	10.05	10.56	9.67	10.18	10.47	11.31	10.16	10.46	11.3

Appendix 7.3 Water Surface Extent Result data for 10 profiles used in this study. U1 is the 1986 land-use and rainfall condition. U2 signifies UMP means Urban Masterplan, UUMP means urban Masterplan +urban sprawl. NF means No forest, LAF means low afforestation and HAF means High afforestation scenario.

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
T. Amadi Rch	2309.546	81.68	90.85	147.33	85.43	285.05	319.27	381.14	284.01	319.94	381.14
T. Amadi Rch	2057.07	55.17	61.61	72.49	57.79	91.32	115.27	180.43	90.91	116.02	180.43
T. Amadi Rch	1847.522	106.43	118.39	134.24	111.27	145.44	151.18	185.14	145.34	151.37	185.14
T. Amadi Rch	1678.48	116.78	123.73	158.28	119.59	190.24	203.46	240.88	190.01	203.89	240.88
T. Amadi Rch	1103.246	57.5	63.9	74.63	60.08	82.92	87.21	99.36	82.85	87.35	99.36
T. Amadi Rch	875.2154	42.97	48.29	57.22	45.01	64.13	67.81	78.25	64.07	67.94	78.25
T. Amadi Rch	595.8615	36.26	43.96	54.78	38.36	63.33	68.76	83.53	63.29	69.02	83.53
Soku Reach	34095.76	595.01	548.17	873.73	622.42	780.38	829.98	1013.66	763.95	811.31	985.67
Soku Reach	33461.04	342.34	338	461.1	343.84	362.24	391.08	759.53	356.54	377.98	729.12
Soku Reach	32806.77	583.63	571.17	702.6	587.94	641.18	674.72	795.44	624.65	663.81	776.97
Soku Reach	32241.93	264.65	257.26	340.9	267.2	298.71	322.52	403.39	288.96	314.82	388.47
Soku Reach	31351.41	1111.79	1104.96	1283.65	1114.36	1173.52	1223.95	1484.54	1155.22	1203.57	1458.63
Soku Reach	30900.3	1186.92	1173.9	1279.71	1190.02	1228.37	1257.38	1396.25	1216.5	1248.01	1367.26
Soku Reach	30640.23	716.98	709.64	850.42	719.52	767.41	804.1	1048.77	752.2	792.57	1000.06
Soku Reach	29281.63	480.2	474.11	558.98	482.3	508.19	532.11	641.46	500.19	521.43	623.01
Soku Reach	28575.42	624.39	616.09	789.26	627.24	683.27	753.37	913.88	654.3	733.32	884.59
Soku Reach	28042.09	421.03	413.9	493.64	423.48	453.72	476.49	736.59	444.37	469.2	675.56
Soku Reach	27124.8	512.86	511.41	535.06	513.36	519.5	524.11	578.64	517.6	522.64	565.12
Soku Reach	26183.71	515.62	499.43	680.48	521.19	589.72	641.32	887.33	568.53	624.8	833.14
Soku Reach	25203.91	840.19	838	863.25	840.95	850.29	857.32	885.01	847.4	855.07	879.83
Soku Reach	24016.2	715.71	712.79	745.56	716.72	729.14	738.46	812.77	725.3	735.48	782.49
Soku Reach	22377.95	981.91	970.98	1192.21	985.66	1059.7	1126.93	1521.12	1032.26	1104.94	1383.96
Soku Reach	20393.28	1721.59	1701.12	1896.93	1727.2	1794.71	1850.77	2080.21	1774.27	1831.75	2028

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Soku Reach	17919	3846.62	3794.11	4389.14	3865.06	4097.86	4264.86	4865.17	4023.79	4212.85	4743.62
Soku Reach	15643.32	4119.88	4048.68	4626.94	4144.31	4437.98	4553.07	4881.78	4316.78	4522.85	4841.61
Soku Reach	14086.8	3864.5	3820.45	4303.53	3881.66	4078.88	4224.44	4551.4	4022.72	4177.49	4498.21
Soku Reach	12100.43	6042.39	6016.68	6279.18	6051.2	6148.2	6217.31	6479.39	6119.91	6195.25	6444.12
Soku Reach	10021.08	4297.48	4246.83	5000.24	4320.41	4647.25	4818.87	5328.36	4562.42	4743.98	5270.65
Soku Reach	6669.989	1716.4	1683.4	2176.13	1727.35	1856.62	1938.24	2813.85	1821.54	1913.75	2646.18
Soku Reach	4694.321	1805.72	1763.71	2320.55	1820.55	2007.41	2178.63	2866.5	1950.23	2121.85	2752.27
Soku Reach	2014.274	1612.76	1563.31	2161.12	1630.83	1883.01	2015.6	2504.98	1814.49	1973.97	2453.2
Sambreiro Rch	9123.329	257.97	273.5	315.37	256.16	324.43	340.41	413.56	323.49	340.4	413.56
Sambreiro Rch	8142.11	104.47	106.43	112.99	104.2	114.4	116.95	125.01	114.25	116.95	125.01
Sambreiro Rch	7668.151	152.72	163.06	190.05	152.28	201.64	215.09	257.21	201.26	215.5	257.21
Sambreiro Rch	7055.343	608.82	630.78	686.33	607.91	709.84	738.49	896.1	709.08	739.71	896.1
Sambreiro Rch	5935.431	250.8	264.09	297.45	250.3	311.86	324.48	455.5	311.42	324.87	455.5
Sambreiro Rch	5450.645	179.85	191.28	219.61	179.56	232.59	246.92	287.56	232.24	247.41	287.56
Sambreiro Rch	4415.756	104.3	115.24	137.94	105.46	152.52	164.92	198.09	152.43	165.52	198.09
Sambreiro Rch	3227.193	217.57	232.41	255.64	221.38	273.75	286.87	321.64	273.77	287.6	321.64
Sambreiro Rch	2595.2	171.82	185.43	203.95	176.16	219.5	248.65	391.65	219.57	252.51	391.65
S.Eleme Rch	15231.35	276.52	283.84	296.1	277.86	305.02	312.33	331.83	305	312.7	331.83
S.Eleme Rch	14635.09	104.61	115.65	134.13	106.64	147.59	158.07	185.41	147.56	158.59	185.41
S.Eleme Rch	13041.89	35.28	42.65	53.6	37.22	62.16	68.37	84.62	62.18	68.71	84.62
S.Eleme Rch	11716.79	705.54	726.96	758.37	711.09	782.17	799.51	842.1	782.21	800.45	842.1
S.Eleme Rch	10548.3	53.21	62.35	98.14	55.6	132.16	144.46	176.22	132.19	145.13	176.22
S.Eleme Rch	9228.045	88.26	92.4	98.48	89.49	103.48	106.93	115.77	103.5	107.13	115.77
S.Eleme Rch	8835.141	41.14	50.57	63.11	44.11	73.2	80.05	104.37	73.24	80.45	104.37
S.Eleme Rch	7651.621	228.15	235.87	247.76	230.59	301.24	320.59	369.72	301.37	321.7	369.72
S.Eleme Rch	6509.708	217.92	225.82	236.49	220.54	245.4	259.85	306.51	245.44	260.96	306.51

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
S.Eleme Rch	5793.06	262.81	294.86	334.1	272.98	362.46	381.64	460.47	362.58	382.75	460.47
S.Eleme Rch	4682.95	754.32	890.48	1089.26	795.92	1280.58	1351.98	1524.22	1281.06	1356.64	1524.22
S.Eleme Rch	3806.595	375.87	386.24	400.57	379.17	412.57	427.29	504.63	412.63	428.52	504.63
S.Eleme Rch	3467.46	533.08	542.75	591.57	536.16	660.74	704.18	823.62	661.03	706.68	823.62
S.Eleme Rch	3018.646	551.96	564.19	597.08	555.93	619.08	642.02	748.02	619.18	646.57	748.02
S.Eleme Rch	2648.755	747.86	784.41	833.83	759.99	875.01	945.81	1172.92	875.19	950.91	1172.92
S.Eleme Rch	2288.26	756.96	842.42	909.74	784.15	951.2	984.78	1101.4	951.38	987.28	1101.4
S.Eleme Rch	2050.328	668.41	718.42	825.51	684.92	918.24	978.71	1175.15	918.67	982.1	1175.15
Rumumasi Reach	5357.174	341.88	356.82	384.06	349.44	405.07	417.49	469.11	404.66	417.76	469.11
Rumumasi Reach	4997.979	363.33	370.95	384.66	367.2	395.19	401.41	455.08	394.98	401.54	455.08
Rumumasi Reach	4579.672	412.32	422.22	440.08	417.34	448.88	453.44	490.15	448.73	453.54	490.15
Rumumasi Reach	3195.744	111.35	119.62	134.18	115.72	145.32	151.42	302.48	145.14	151.58	302.48
Rumumasi Reach	2923.519	607.4	638.89	694.29	623.72	733.41	761.72	857.74	732.84	762.59	857.74
Rumumasi Reach	2584.753	610.47	672.33	794.49	643.35	903.2	974.37	1242.02	901.59	976.31	1242.02
Rumumasi Reach	2217.213	71.68	83.88	102.98	77.79	118.39	152.41	239.74	117.29	153.31	239.73
Rumumasi Reach	1878.588	97.34	108.82	126.69	102.48	140.01	148.05	364.65	139.85	148.33	364.64
Rumumasi Reach	1630.329	83.26	175.97	246.84	154.44	334.09	389.54	522.49	332.96	391.01	522.48
Rumumasi Reach	778.4335	84.45	95.51	112.77	88.52	126.09	136.1	280.09	125.98	137.82	280.09
Rumumasi Reach	473.6282	44.44	51.48	62.48	46.38	71.16	127.39	239.69	71.12	133.15	239.68
PhC Trib Rch	4665.434	964.02	975.17	991.21	966.36	1001.08	1007.05	1023.06	1001.04	1007.34	1023.06
PhC Trib Rch	4482.177	909.36	917.33	928.79	911.04	936.66	942.93	959.42	936.61	943.23	959.42
PhC Trib Rch	4233.093	922.15	953.63	987.97	929.34	1007.01	1022.17	1073.27	1006.9	1022.91	1073.27
PhC Trib Rch	3941.49	656.35	672.39	696.37	659.72	712.87	725.99	781.77	712.78	726.63	781.76
PhC Trib Rch2	2557.172	361.28	455.1	561.34	373.7	600.83	629	806.71	600.68	630.41	806.71
PhC Trib Rch2	2219.451	411.01	494.83	644.97	430.94	698.55	743.22	906.15	698.39	746.25	906.14
PhC Trib Rch2	1858.75	562.93	644.45	818.53	582.99	883.09	933.83	1063.69	882.94	936.58	1063.68

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
PhC Trib Rch2	1203.888	446.41	534.87	685.8	468.79	785.62	848.45	1004.27	785.51	851.23	1004.26
PhC River 3 Rch	3911.49	3002.73	3114.99	3254.52	3038.44	3378.38	3467.08	3751.41	3378.97	3472.21	3751.41
PhC River 3 Rch	3500.946	2963.28	3097.64	3347.49	3008.61	3518.54	3661.91	4081.1	3519.27	3671.57	4081.1
PhC River 3 Rch	3118.827	3274.83	3584.45	3987.14	3368.96	4387.66	4732.95	5410.11	4389.71	4751.48	5410.11
PhC River 3 Rch	2647.605	3657.67	3914.64	4206.09	3735.94	4466.41	4668.22	5184.6	4467.63	4680.79	5184.6
PhC Rv3 Rch	1318.699	1925.37	1990.4	2169.39	1954.37	2384.96	2694.19	3162.07	2386.62	2701.79	3162.07
PhC Rv3 Rch	1104.487	1874.36	1904.2	2201.22	1883.71	2451.43	2630.06	3361.01	2452.29	2644.32	3361.01
PhC Rv3 Rch	794.874	2162.07	2301.6	2595.98	2212.73	2745.75	2853.89	3081.62	2746.29	2860.83	3081.62
PhC River 2 Rch	5693.304	1319.3	1427.31	1621.95	1354	1922.21	2043.81	2453.48	1922.88	2053.45	2453.48
PhC River 2 Rch	5257.414	1284.45	1314.94	1408.99	1288.92	1464.08	1499.72	1634.4	1464.27	1501.68	1634.4
PhC River 2 Rch	4436.802	1566.4	1707.9	1951.91	1611.55	2140.69	2301.32	2756.38	2141.22	2309.51	2756.38
PhC River 2 Rch	3818.894	1178.25	1218.02	1346.31	1186.82	1482.78	1667.91	1799.71	1483.52	1671.02	1799.71
PhC River 2 Rch	3163.156	2115.84	2317.34	2681.1	2174.79	3237.51	3518.29	4047.55	3240.46	3532.09	4047.55
PhC River 2 Rch	2565.354	2481.01	2898.32	3465.53	2573.77	3896.41	4283.53	4834.83	3897.92	4293.25	4834.84
PhC River 2 Rch	2017.433	2223.09	2504.18	2937.36	2332.48	3524.22	3839.91	4657.47	3526.46	3855.46	4657.47
PhC River 1 Rch	10846.61	351.31	364.38	383.55	354.98	480.2	549.81	995.95	479.69	553.68	995.93
PhC River 1 Rch	10244.22	563.27	631.79	647.55	607.94	659.67	667.61	686.44	659.61	667.98	686.44
PhC River 1 Rch	9710.716	410.31	429.48	459.92	414.87	483.08	498.53	527.82	482.96	499.25	527.82
PhC River 1 Rch	8587.027	1222.28	1275.26	1352.28	1235.95	1422.28	1492.04	1726.17	1421.89	1495.37	1726.16
PhC River 1 Rch	7690.577	1604.37	1706.17	1806.76	1630.09	1843.31	1865.89	1925.58	1843.14	1866.96	1925.58
PhC River 1 Rch	7306.689	1973.88	1990.59	2014.09	1977.92	2031.25	2043.49	2076.63	2031.15	2044.07	2076.63
PhC River 1 Rch	6776.999	1088.09	1192.13	1533.6	1103.84	1619.39	1671.39	1944.86	1619	1673.87	1944.85
PhC River 1 Rch	6264.194	935.27	963	1013.16	941.86	1097.11	1154.75	1410.52	1096.68	1157.5	1410.5
PhC River 1 Rch	5899.262	1196.67	1236.27	1293.97	1206.04	1336.15	1366.98	1442.54	1335.92	1368.49	1442.54
PhC River 1 Rch	5461.963	1576.34	1625.19	1691.01	1587.87	1736.06	1768.73	1856.91	1735.82	1770.29	1856.91
PhC River 1 Rch	4882.684	263.05	273.84	289.49	265.55	321.07	371.23	461.02	320.7	373.72	461.01

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
PhC River 1 Rch	4447.399	252.1	260.94	273.63	253.94	282.25	289.19	307.76	282.2	289.53	307.76
PhC Rv1 rch2	1914.555	852.99	894.57	958.86	863.6	1013.55	1048.52	1137.37	1013.7	1050.46	1137.37
PhC Rv1 rch2	1414.925	927.85	936.1	951.15	930.59	964.1	972.42	1017.96	964.14	972.88	1017.96
PhC Rv1 rch2	1070.069	977.04	985.66	997.56	979.9	1049.54	1065.47	1151.79	1049.6	1066.36	1151.79
PhC Rv1 rch2	728.6349	1079.58	1101.49	1131.41	1086.84	1159.04	1200.07	1338.89	1159.23	1202.3	1338.89
Okrika Rch	13665.25	155.38	144.27	252.44	167.69	153.12	187.55	276.43	155.02	191.09	276.43
Okrika Rch	12794.63	361.69	359.76	496.31	363.84	361.35	367.36	533.52	361.68	367.96	533.52
Okrika Rch	12072.56	420.69	405.88	571.73	437.15	418.38	464.41	630.49	420.9	469	630.49
Okrika Rch	11764	760.39	757.51	792.85	763.47	759.95	767.61	844.26	760.44	768.31	844.26
Okrika Rch	11324.64	293.35	283.75	464.81	303.63	292	320.24	520.41	293.64	323.01	520.41
Okrika Rch	10998.09	792.02	783.63	867	801.35	790.83	816.96	886.22	792.26	819.57	886.22
Okrika Rch	10578.72	36.62	35.73	44.92	37.69	37.19	40.26	47.76	37.34	40.56	47.76
Okrika Rch	10243.39	175.85	174.71	186.53	177.16	176.16	179.9	190.16	176.35	180.26	190.16
Okrika Rch	9061.025	76.26	74.46	103.86	78.47	77.97	84.43	134.53	78.28	85.03	134.53
Okrika Rch	8374.236	183.58	181.72	206.52	186.38	189.53	198.01	228.79	189.86	198.74	228.79
Okrika Rch	7687.396	103.37	100.58	150.13	110.89	131.36	145.31	202.21	131.77	146.38	202.21
Okrika Rch	7072.159	226.22	225.93	233.62	227.07	230.13	232.9	476.57	230.21	233.11	476.57
Okrika Rch	6655.038	111.39	110.9	126.03	113.08	119.65	125.18	139.58	119.79	125.59	139.58
Okrika Rch	5649.987	244.08	243.83	253.47	245.15	249.79	253.36	267.49	249.88	253.63	267.49
Okrika Rch	5163.031	65.47	65.43	84.34	67.59	79.23	87.27	241.8	79.39	102.56	241.8
Okrika Rch	4237.385	246.4	246.56	349.04	248.36	342.35	355.84	406.86	342.62	356.37	406.86
Okrika Rch	3678.697	59.93	61.1	77.68	61.95	78.38	85.84	102.07	78.49	86.32	102.07
Okrika Rch	3059.927	123.74	128.6	136.96	125.46	142.45	147.02	185.4	142.49	147.32	185.4
Okrika Rch	2781.317	204.58	209.12	216.14	206.1	222.16	240.7	294.15	222.2	241.9	294.15
Okrika Rch	2379.053	305.46	312.69	323.09	307.8	331.22	337.06	370.5	331.27	337.4	370.5
Okrika Rch	2095.073	443.6	452.64	465.35	446.5	475.27	481.99	535.33	475.32	482.39	535.33

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Odual Tributary	2003.022	365.07	515.98	579.66	371.07	594.98	702.74	1106.8	590.18	702.89	1106.9
Odual Tributary	1487.593	921.25	1056.21	1076.46	930.78	1080.29	1107.39	1221.15	1079.09	1107.44	1221.21
Odual Tributary	909.9347	367.31	482.88	502.49	375.33	506.2	532.62	596.09	505.05	532.68	596.11
N.Eleme Rch	3551.777	161.21	168.57	174.77	166.04	185.71	200.93	234.41	186.27	202.28	234.41
N.Eleme Rch	3102.823	153.44	269.89	281.3	265.7	290.47	295.17	309.27	290.65	295.53	309.27
N.Eleme Rch	2605.724	66.51	75.81	88.08	71.07	97.26	102.25	116.18	97.45	102.65	116.18
N.Eleme Rch	1887.28	77.74	95.23	135.89	85.26	180.15	201.79	361.84	179.87	202.55	361.84
N.Eleme Rch	1361.515	293.91	358.25	420.97	335.56	467.6	489.16	621.31	467.3	489.9	621.31
N.Eleme Rch	1063.356	281.66	324.49	389.95	299.76	432.92	453.03	507.06	432.64	453.72	507.06
N.Eleme Rch	624.9445	99.71	192.86	317.74	142.68	425.9	442.04	492.53	425.79	442.63	492.53
Lwr Choba Rch	3117.347	733.08	738.56	746.26	734.18	752.05	756.27	768.48	752.01	756.43	768.61
Lwr Choba Rch	2630.421	668.12	671.06	675.04	668.71	677.64	679.54	685.03	677.62	679.61	685.09
Lwr Choba Rch	2210.917	661.74	663.92	666.87	662.17	668.81	670.22	674.28	668.79	670.27	674.33
Lwr Choba Rch	1505.881	1675.77	1677.6	1680.15	1676.13	1681.81	1683.02	1686.52	1681.8	1683.07	1686.56
Lwr Choba Rch	1177.626	1494.41	1495.77	1497.7	1494.68	1498.95	1499.86	1502.5	1498.94	1499.9	1502.53
Lwr Choba Rch	716.0721	907.88	928.07	951.22	912.74	966.59	978.86	1013.51	966.46	979.48	1013.78
Lw Eagle Isl Rch	4028.788	1516.17	1747.63	2039.79	1580.32	2298.45	2493.25	2857.45	2298.38	2500.82	2857.42
Lw Eagle Isl Rch	3553.737	975.83	1292.66	1666.46	1088.98	1967.98	2242.77	3078.42	1967.98	2257.2	3078.39
Lw Eagle Isl Rch	2981.277	2188.33	2524.06	2980.47	2293.99	3497.16	3780.1	4283.92	3497.23	3792.11	4283.9
Lw Eagle Isl Rch	2431.181	1899.36	2066.07	2262.8	1934.48	2456.19	2640.69	3319.33	2456.24	2652.92	3319.29
Lw Eagle Isl Rch	1818.94	1767.87	2118.9	2653.39	1873.7	3101.99	3455.79	4452.25	3102.13	3474.02	4452.22
Lw Eagle Isl Rch	1129.461	1054.44	1315.24	1551.16	1102.21	1799.85	1935.64	2149.96	1800.01	1943.92	2149.95
Lw Eagle Isl Rch	535.0954	346.94	403.24	482.25	363.62	570.13	707.29	1070.82	570.31	716.51	1070.82
Kor Rive Rch	4708.004	649.56	654.54	816.3	647.64	759.36	804.48	941.7	788.7	836.15	2018.36
Kor Rive Rch	4163.468	630.78	635.63	655.9	629.14	646.86	654.03	703.55	651.52	659.05	1557.48
Kor Rive Rch	3440.388	544.4	587.97	767.74	532.79	722.9	751.56	978.16	741.48	795.08	1723.18

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Kor Rive Rch	2678.573	461.78	480.7	583.28	455.46	537.35	573.9	640.67	561.18	598.32	776.08
Kor Rive Rch	1504.354	377.05	383.37	477.01	374.97	468.93	475.3	493.99	473.1	479.8	702.09
Kor Rive Rch	749.9553	120.35	128.11	160.21	117.88	144.51	156.97	188.45	152.68	165.62	349.02
Iwofe Rch	2657.526	27.85	32.84	36.31	29.29	38.02	40.12	46.08	37.98	40.18	46.08
Iwofe Rch	2405.32	87.3	141.19	186.12	101.39	214.07	271.44	435.84	213.07	273.59	435.83
Iwofe Rch	1987.4	88.75	97.78	105.89	91.08	110.51	115.21	128.5	110.43	115.4	128.5
Iwofe Rch	1368.51	228.74	248.97	266.45	234.72	275.61	282.76	302.89	275.5	283.04	302.89
Iwofe Rch	644.0602	233.24	330.67	413.46	255.76	445.61	475.75	585.36	445.13	476.51	585.36
Iwofe Rch	374.4696	156.23	176.94	196.18	161.48	207.35	218.51	245.66	207.17	218.92	245.65
PhC Habour	11720.27	35.9	42.41	46.95	37.77	49.19	51.92	59.72	49.13	52.01	59.72
PhC Habour	11368.09	243.6	287.76	329.23	254.37	352.91	381.6	530.61	352.52	383.34	530.61
PhC Habour	10421.94	209.67	252.03	324.75	218.26	366.77	408.75	523.44	366.1	410.41	523.44
PhC Habour	9685.051	503.57	516.45	528.55	506.8	535.54	542.52	580.84	535.43	542.8	580.84
PhC Habour	9272.59	540.55	549.25	557.43	542.73	562.16	566.87	580.13	562.08	567.06	580.13
PhC Habour	8810.765	352.29	376.09	400.08	357.39	413.95	427.79	466.68	413.74	428.34	466.68
Isaka Lower Rch	7499.176	146.48	208.54	288.07	162.1	334.49	380.18	645.24	333.78	382.01	645.24
Isaka Lower Rch	7137.471	109.63	126.56	143.4	113.73	156.74	172.62	249.77	156.51	173.27	249.76
Isaka Lower Rch	6491.283	375.6	456.8	625.43	391.29	756.13	893.07	1372.02	754.14	899.35	1372
Isaka Lower Rch	5762	633.28	867.35	1203.54	661.16	1294.57	1422.86	1987.93	1292.8	1428.9	1987.9
Isaka Lower Rch	5223.925	907.34	980.34	1100.89	922.24	1244.13	1333.49	1565.54	1242.85	1337.18	1565.53
Isaka Lower Rch	4238.011	573.7	639.27	714.26	588.2	768.86	790.08	856.4	768.1	790.56	856.39
Isaka Lower Rch	3629.504	98.55	122.25	148.39	103.67	163.63	178.23	284.9	163.43	178.84	284.89
Isaka Lower Rch	2256.603	217.95	232.76	251.08	220.8	263.39	275.26	321.5	263.24	275.78	321.5
Isaka Lower Rch	1248.921	194.34	204.78	218.32	196.26	227.02	235.14	256.74	226.92	235.5	256.74
Elelenwo Reach	2859.101	221.46	234.24	260.39	228.05	279.06	286.78	310.06	278.91	287.01	310.06
Elelenwo Reach	2569.424	148.63	153.81	175.09	151.33	232.45	299.55	316	229.26	299.71	316

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Elelenwo Reach	2247.295	90.3	95.99	107.55	93.38	121.35	129.12	153.21	121.22	129.36	153.21
Elelenwo Reach	1641.735	170.86	178.92	206.95	171.79	227.83	238.2	295.15	227.64	238.52	295.15
Elelenwo Reach	1239.382	247.36	258.04	282.04	251.71	308.37	321.5	354.25	308.14	321.9	354.25
Elelenwo Reach	925.7126	258.91	286.36	333.88	270.08	350.44	357.67	378.01	350.31	357.9	378.01
Egbema Upper Rch	7620.897	763.54	753.06	807.21	724.14	762.29	791.44	935.9	760.36	788.65	934.28
Egbema Upper Rch	6975.507	1255.91	1231.7	1316.07	1163.87	1254.19	1302.99	1397.3	1249.55	1300.58	1396.87
Egbema Upper Rch	6615.183	1190.17	1178.18	1231.51	1144.29	1189.79	1221.98	1336.57	1187.42	1220.17	1336.39
Egbema Upper Rch	6056.989	1772.3	1745.52	1819.29	1639.5	1775.01	1815.55	1862.15	1769.16	1814.78	1861.44
Egbema Upper Rch	5797.456	1246.92	1239.51	1273.36	1143.06	1249.21	1269.32	1344.93	1247.35	1268.39	1343.47
Egbema Upper Rch	5091.818	1002.93	994.8	1102.38	921.9	1019.98	1094.18	1290.99	1015.67	1090.51	1287.2
Egbema Upper Rch	4798.4	1046.61	1044.18	1075.6	1012.29	1055.07	1074.47	1134.39	1053.26	1073.79	1133.78
Egbema Upper Rch	4247.958	1032.27	1038.54	1157.68	930.61	1071.99	1164.91	1412.78	1066.05	1157.98	1405.13
Egbema Upper Rch	3888.238	794.53	837.45	893.06	763.35	865.48	904.15	990.02	862.65	903.6	989.44
Egbema Lower Rch	3066.631	345.13	458.52	487.49	350.07	493	514.73	583.51	491.31	514.77	583.58
Egbema Lower Rch	2515.038	472.82	527.67	542.92	475.48	545.77	567	632.36	544.96	567.05	632.41
Egbema Lower Rch	2087.512	341.2	418.99	443.55	345.8	452.37	511.26	958.45	447.45	511.41	958.8
Egbema Lower Rch	1587.756	837.49	1237.37	1319.21	867.51	1348.29	1431.48	1791.49	1328.97	1431.68	1791.81
Egbema Lower Rch	1011.06	951.58	1230.81	1305.04	963.47	1341.71	1446.76	1810.8	1314.47	1447.03	1811.03
Egbema Lower Rch	600.1398	658.78	929.05	977.02	666.59	1004.79	1060.14	1268.16	983.23	1060.28	1268.28
Egbema Lower Rch	219.8786	182.21	204.95	210.34	183.44	211.38	228.35	289.07	211.08	228.41	289.11
Eagle Isl Rch	20175.23	375.18	406.42	453.35	376.49	474.33	517.95	686.48	472.58	518.6	686.48
Eagle Isl Rch	19541.11	645.77	670.65	710.4	646.79	731.07	791.05	1028.46	728.73	793.07	1028.45
Eagle Isl Rch	18815.8	536.85	565.73	614.98	538.09	634.58	670.91	754.95	633.11	671.46	754.95
Eagle Isl Rch	18228.53	765.06	809.94	877.34	767	897.16	933.94	1067.63	895.68	934.5	1067.62
Eagle Isl Rch	17633.08	507.96	546.73	611.74	509.68	634.91	696.92	872	633.22	697.98	872
Eagle Isl Rch	17011.49	648.31	687.85	786.53	650.12	840.98	937.74	1166.88	837.17	938.89	1166.87

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Eagle Isl Rch	15623.3	567.88	641.01	817.92	571.62	892.78	1030.55	1583.73	887.82	1033.73	1583.72
Eagle Isl Rch	15122.23	311.38	342.63	417.8	313.19	488.66	602.77	905.43	484.55	604.96	905.42
Eagle Isl Rch	14395.02	310.85	331.51	385.32	311.45	426.52	559.87	798.76	423.19	561.37	798.76
Eagle Isl Rch	13377.85	211.16	220.25	233.72	211.77	238.56	271.88	402.68	238.33	272.77	402.68
Eagle Isl Rch	12545	338.17	362.57	398.78	339.99	415.72	473.82	663.9	414.89	475.68	663.89
Eagle Isl Rch	11194.69	173.73	182.22	190.7	174.8	194.68	199.32	210.95	194.55	199.44	210.95
Eagle Isl Rch	10397.37	442.63	478.05	532.76	445.3	559.03	588.41	673.25	558.32	589.34	673.25
Eagle Isl Rch	9679.32	360.84	397.22	456.45	364.95	521.29	592.22	784.12	519.62	594.42	784.11
Eagle Isl Rch	9296.871	435.98	445.78	460.35	437.12	467.71	494.45	624.97	467.54	495.79	624.96
Eagle Isl Rch	8156.481	224.13	235.99	253.53	225.71	263.25	272.8	299.09	263.07	273.16	299.09
Eagle Isl Rch	7004.388	259.88	269.61	283.9	261.63	293.54	301.52	469.68	293.46	301.88	469.67
Eagle Isl Rch	6301.9	759.6	870.87	1066.73	775.8	1176.39	1243.74	1632.28	1175.77	1246.78	1632.27
Eagle Isl Rch	5171.876	429.96	471.74	515.71	440.02	617.88	654.04	849.9	617.63	655.76	849.88
Eagle Isl Rch	3607.002	802.48	894.11	978.66	823.94	1026.34	1062.59	1408.13	1026.16	1064.38	1408.12
Eagle Isl Rch	2524.504	696.91	744	825.76	707.98	906.56	1100.98	1445.24	906.29	1109.11	1445.22
Eagle Isl Rch	1789.479	506.88	542.06	625.04	515.66	706.01	794.66	1258.21	705.88	799.51	1258.18
Eagle Isl Rch	612.6847	977.73	1186.63	1393.23	1031.78	1599.41	1715.97	2047.4	1599.29	1722.69	2047.37
Dutch Isl Rch	3217.171	569.48	584.99	627.93	567.58	637.53	654.63	929.96	636.45	654.63	929.96
Dutch Isl Rch	2847.968	778.51	783.65	797.87	777.88	801.05	806.71	829.45	800.69	806.71	829.45
Dutch Isl Rch	2638.333	566.02	571.61	587.08	565.34	590.54	596.7	629.28	590.15	596.7	629.28
Dutch Isl Rch	2284.159	276.21	282.9	301.4	275.39	305.53	312.83	335.75	305.06	312.83	335.75
Dutch Isl Rch	1930.845	591.13	670.76	734.99	580.68	756.24	815.76	986.18	752.46	815.76	986.18
Dutch Isl Rch	1520.077	870.99	909.24	982.68	864.69	999.02	1028.03	1219.36	997.19	1028.03	1219.36
Dutch Isl Rch	1231.084	578.44	605.83	672.86	575.11	683.45	702.22	781.77	682.26	702.22	781.77
Dutch Isl Rch	923.5763	114.72	118.88	130.63	114.21	133.24	137.89	239.14	132.95	137.89	239.14
Degema Upper Rch	10015.86	1164.2	1146.56	1273.79	1120.46	1250.41	1285.05	1376.86	1247.47	1284	1375.11

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Degema Upper Rch	9447.894	697.07	703.61	847.68	672.49	843.93	854.17	883.83	843.15	853.95	883.58
Degema Upper Rch	8176.194	1058.47	1073.39	1113.79	1055.69	1114.37	1141.92	1224.16	1113.42	1141.64	1224.08
Degema Upper Rch	7296.695	3216.18	3294.45	3475.74	3214.05	3483.73	3627.55	3940.27	3479.69	3627.1	3939.34
Degema Upper Rch	7110.268	3317.16	3472.84	3719.11	3316.55	3728.95	3799.3	3940.48	3724.47	3798.92	3940.24
Degema Upper Rch	5995.249	3755.67	3839.22	4002.73	3758.96	4012.9	4110.72	4262.65	4009.21	4110.47	4262.41
Degema Lower Rch	3056.964	2034.57	2163.3	2710.18	2075.96	2275.42	2567.71	2945.28	2251.15	2544.37	2941.3
Degema Lower Rch	1958.294	2008.03	2106.36	2484.98	2035.86	2223.69	2427.77	2862.6	2190.19	2415.67	2856.24
Degema Lower Rch	1459.966	1553.3	1619.78	1823.62	1573.33	1689.25	1762.63	2263.34	1679.89	1756.51	2251.28
Degema Lower Rch	655.1443	2150.75	2218.61	2580.41	2174.66	2407.51	2517.14	2899.51	2386.38	2508.83	2892.83
Choba Rch	12556.62	335.59	365.15	467.57	341.54	511.71	538.59	629.09	511.36	539.63	632.64
Choba Rch	11981.62	319.98	366.44	453.51	329.33	497.86	526.23	733.32	497.48	527.32	735.02
Choba Rch	11356.44	253.79	273.35	302.53	257.71	338.98	362.87	434.39	338.65	363.78	435.21
Choba Rch	10501.81	151.85	253.64	583.45	155.21	741.79	847.88	1267.98	739.58	851.6	1271.7
Choba Rch	9117.822	169.08	184.2	202.82	172.09	215.77	224.47	320.67	215.7	224.83	322.93
Choba Rch	7221.321	1027.32	1050.09	1113.91	1032.51	1116.56	1139.16	1410.38	1115.97	1139.77	1329.44
Choba Rch	6630.73	559.8	594.72	795.46	568.64	762.23	869.37	1127.53	758.75	871.36	1097.97
Choba Rch	5315.833	646.53	703.21	1372.32	664.95	1295.76	1440.93	1736.93	1290.13	1443.26	1673.73
Choba Rch	3529.868	1105.56	1207.56	1800.63	1120.42	1690.14	1881	2618.72	1682.54	1884.04	2437.59
Choba Rch	2739.644	871.53	894.77	1478.76	879.77	1383.1	1538.35	1996.19	1377.08	1540.64	1850.92
Choba Rch	1148.281	1334.11	1382.05	2091.27	1350.97	1961.88	2152.21	2653.96	1953.39	2154.36	2440.66
Choba Rch	589.6992	1773.26	1798.73	2192.97	1782.37	2134.5	2228.66	2538.65	2130.31	2230.06	2415.79
Buguma Rch	22169.42	1946.52	2193.07	2541.16	1977.9	2572.49	2701.19	2975.4	2564.58	2700.93	2975.26
Buguma Rch	20077.09	4266.55	4401.42	4625.89	4280.09	4635.76	4676.41	4789.79	4633.27	4676.31	4789.72
Buguma Rch	19287.01	2248.74	2296.48	2649.73	2253.92	2667.14	2749.13	3089.61	2662.27	2748.94	3089.34
Buguma Rch	14320.91	1551.16	1762.34	2453.07	1572.43	2489.58	2655.43	3136.67	2480.56	2654.88	3136.45
Buguma Rch	13044.47	1391.01	1496.82	1778.91	1402.37	1803.33	1891.06	2086.54	1797.29	1890.87	2086.41

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Buguma Rch	11091.03	646.82	742.39	1041.24	660	1060.87	1128.9	1566.77	1056.03	1128.75	1566.51
Buguma Rch	8542.064	709.19	755.58	1263.33	714.62	1284.87	1340.07	1422.53	1279.54	1340.01	1422.47
Buguma Rch	6771.962	1021.31	1101.08	1227.88	1030.72	1239.85	1290.49	1430.35	1236.89	1290.37	1430.2
Buguma Rch	5756.395	557.58	722.56	885.87	572.99	899.99	962.62	1188.97	896.49	962.46	1188.77
Buguma Rch	4494.115	519.37	684.63	897.03	537.63	917.99	1016.74	1260.74	912.8	1016.44	1260.5
Buguma Rch	3652.478	589.1	632.19	715.64	593.82	724.16	758.92	846.07	722.05	758.84	845.99
Buguma Rch	2207.349	296.43	308.71	393.72	297.79	407.49	463.67	677.73	404.08	463.54	677.62
Buguma Rch	1463.724	440.43	466.31	517.34	444.04	523.84	556.28	647.99	522.23	556.2	647.95
Buguma Rch	293.3568	521.91	534.93	571.57	523.29	575.6	592.32	636.43	574.6	592.28	636.4
Bori River Rch	11178.96	1458.82	1504.98	1613.39	1457.43	1603.88	1649.72	1802.87	1598.25	1645.82	1777.41
Bori River Rch	7423.903	1952.26	2035.12	2619.01	1950.1	2567.37	2776.25	3416.43	2536.51	2759.99	3287.77
Bori River Rch	5467.596	895.55	936.79	1108.88	894.34	1091.53	1191.53	1523.59	1081.26	1181.66	1473.9
Bori River Rch	4403.423	766	796.13	883.47	765.09	875.59	912.32	1040.62	870.92	909.42	999.7
Bori River Rch	2524.635	1081.77	1185.59	1634.61	1079.51	1597.65	1711.84	2063.93	1574.17	1704.44	2013.66
Bori River Rch	1561.587	565.97	607.68	733.28	564.69	719.57	790.38	1011.66	711.42	783.65	990.69
Bori River Rch	543.6863	87.65	94.74	111.57	87.44	110.04	116.45	136.36	109.08	116.17	133.07
Bonny River Rch	16321.99	2092.69	2138.79	2313.21	2100.68	2466.02	2609.23	3035.9	2466.8	2615.71	3035.9
Bonny River Rch	15959.9	2178.31	2191.49	2256.71	2182.5	2311.89	2354.89	2670.89	2312.2	2357.4	2670.89
Bonny River Rch	15252.99	2783.07	2987.6	3354.85	2851.82	3656.37	3774.72	4158.61	3657.47	3780.38	4158.61
Bonny River Rch	14245.93	2868.6	3137.84	3452.93	2973.47	3758.32	4007.85	4753.44	3759.88	4023.94	4753.44
Bonny River Rch	13232.1	3039.19	3236.46	3684.61	3091.82	4088.67	4345.64	5087.52	4090.62	4357.44	5087.52
Bonny River Rch	12346.08	3251.35	3694.4	4371.52	3421.96	4800.31	5206.83	5782.87	4802.39	5219.28	5782.87
Bonny River Rch	11616.86	3467.11	3735.94	4241.28	3563.22	4687.06	5090.16	6008.57	4690.22	5109.18	6008.57
Bonny River Rch	11070.12	3686.85	3953.39	4542.32	3755.25	4796.1	5074.73	5611.51	4797.4	5098.59	5611.51
Bonny River Rch	10425.34	4870.92	5333.59	5958.57	5034.82	6179.6	6359.83	6777.95	6180.76	6371.71	6777.95
Bonny River Rch	9196.691	6901.73	7008.1	7319.69	6940.76	7702.03	8037.7	8372.49	7704.72	8046.96	8372.49

Reach	River Station	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Bonny River Rch	7985.233	8510.75	8603.91	8742.17	8540.61	8852.9	8903.33	9037.71	8853.43	8906.14	9037.71
Bonny River Rch	6473.635	9249.86	9419.3	9648.95	9297.81	9811.79	9962.69	10293.27	9812.67	9975.33	10293.27
Bonny River Rch	5316.221	9601.88	9889.51	10264.39	9690.59	10631.07	10845.27	11215.64	10632.92	10856.2	11215.64
Bonny River Rch	4022.241	7993.78	8297.52	8824.79	8073.47	9229.13	9414.06	10279.09	9230.65	9429.25	10279.09
Bonny River Rch	2471.691	6048.51	6397.47	6907.86	6125.46	7339.17	7621.88	8805.51	7340.95	7648.75	8805.51
Bonny River Rch	1268.273	3946.22	4089.25	4401.9	3985.33	4696.82	5074.14	6114.11	4698.62	5092.06	6114.11
Bonny River Rch	314.701	3229.46	3325.01	3638.99	3254.3	4082.3	4434.94	5319.57	4084.76	4460.46	5319.57
Abua Rch	5049.264	3955.97	3846.61	4162.47	3594.33	3939.52	4121.13	4580.44	3920.72	4114.21	4574.23
Abua Rch	4412.543	2910.15	2841.39	3081.74	2667.32	2898.69	3036.33	3530.97	2886.54	3028.75	3521.96
Abua Rch	3617.452	2128.29	2062.3	2274.29	1767.99	2116.78	2237.47	2735.76	2105.19	2231.32	2728.8
Abua Rch	2596.925	2484.4	2346.15	2835.51	1979.24	2460.2	2771.91	3318.43	2435.92	2761.53	3310.98
Abua Rch	1425.898	1308.37	1249.77	1493.38	1111.93	1298.06	1445.55	1728.78	1287.78	1437.56	1723.83
Abua Rch	887.2714	1035.9	985.48	1151.09	851.16	1026.72	1121.81	1426.03	1017.65	1116.93	1420.41

Appendix 7.4 Channel Velocity result data for 10 profiles used in this study. W.S means water surface elevation. U1 is the 1986 land-use and rainfall condition. U2 signifies UMP means Urban Masterplan UMP means Urban Masterplan, UUMP means urban Masterplan +urban sprawl. NF means No forest.

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
T. Amadi Rch	2309.546	0.4	0.45	0.52	0.42	0.52	0.5	0.48	0.52	0.5	0.48
T. Amadi Rch	2057.07	0.61	0.68	0.8	0.64	0.89	0.93	1	0.89	0.93	1
T. Amadi Rch	1847.522	0.32	0.36	0.42	0.34	0.48	0.5	0.57	0.48	0.5	0.57
T. Amadi Rch	1678.48	0.23	0.27	0.34	0.25	0.39	0.42	0.49	0.39	0.42	0.49
T. Amadi Rch	1103.246	0.62	0.68	0.81	0.65	0.91	0.95	1.07	0.91	0.95	1.07
T. Amadi Rch	875.2154	0.88	0.97	1.15	0.92	1.28	1.33	1.48	1.28	1.33	1.48
T. Amadi Rch	595.8615	1.53	1.49	1.6	1.59	1.68	1.66	1.66	1.68	1.65	1.66
Soku Reach	34095.76	0.37	0.37	0.43	0.38	0.4	0.41	0.47	0.39	0.41	0.46
Soku Reach	33461.04	0.51	0.49	0.64	0.51	0.58	0.62	0.68	0.56	0.61	0.67
Soku Reach	32806.77	0.33	0.32	0.46	0.34	0.39	0.43	0.54	0.38	0.42	0.52
Soku Reach	32241.93	1.27	1.27	1.28	1.27	1.27	1.28	1.31	1.27	1.28	1.3
Soku Reach	31351.41	0.15	0.15	0.19	0.15	0.17	0.18	0.2	0.17	0.18	0.2
Soku Reach	30900.3	0.19	0.18	0.23	0.19	0.21	0.22	0.25	0.2	0.22	0.25
Soku Reach	30640.23	0.33	0.32	0.38	0.33	0.36	0.38	0.4	0.35	0.37	0.4
Soku Reach	29281.63	0.43	0.42	0.55	0.43	0.48	0.52	0.63	0.47	0.51	0.61
Soku Reach	28575.42	0.34	0.33	0.43	0.34	0.38	0.41	0.49	0.37	0.4	0.48
Soku Reach	28042.09	0.59	0.58	0.72	0.6	0.65	0.69	0.78	0.63	0.68	0.78
Soku Reach	27124.8	0.38	0.37	0.51	0.38	0.44	0.48	0.61	0.42	0.47	0.59
Soku Reach	26183.71	0.54	0.53	0.65	0.55	0.59	0.63	0.7	0.58	0.62	0.69
Soku Reach	25203.91	0.26	0.25	0.35	0.26	0.3	0.33	0.42	0.29	0.32	0.4
Soku Reach	24016.2	0.34	0.33	0.45	0.35	0.39	0.43	0.54	0.38	0.41	0.52
Soku Reach	22377.95	0.28	0.27	0.36	0.28	0.32	0.34	0.42	0.31	0.33	0.41
Soku Reach	20393.28	0.18	0.18	0.23	0.18	0.2	0.22	0.28	0.2	0.22	0.27
Soku Reach	17919	0.1	0.1	0.12	0.1	0.11	0.11	0.14	0.1	0.11	0.13

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Soku Reach	15643.32	0.08	0.08	0.1	0.08	0.09	0.1	0.12	0.09	0.09	0.12
Soku Reach	14086.8	0.09	0.09	0.11	0.09	0.1	0.11	0.13	0.1	0.11	0.13
Soku Reach	12100.43	0.05	0.05	0.06	0.05	0.06	0.06	0.08	0.05	0.06	0.08
Soku Reach	10021.08	0.07	0.07	0.09	0.07	0.08	0.09	0.11	0.08	0.08	0.1
Soku Reach	6669.989	0.2	0.19	0.23	0.2	0.22	0.23	0.24	0.21	0.23	0.24
Soku Reach	4694.321	0.2	0.19	0.24	0.2	0.22	0.23	0.26	0.21	0.23	0.26
Soku Reach	2014.274	0.32	0.31	0.38	0.32	0.35	0.37	0.42	0.34	0.36	0.42
Sambreiro Rch	9123.329	0.27	0.29	0.35	0.27	0.36	0.38	0.43	0.36	0.38	0.43
Sambreiro Rch	8142.11	2.06	2.13	2.24	2.05	2.27	2.33	2.46	2.27	2.33	2.46
Sambreiro Rch	7668.151	0.48	0.49	0.53	0.47	0.51	0.51	0.52	0.51	0.51	0.52
Sambreiro Rch	7055.343	0.08	0.09	0.1	0.08	0.1	0.11	0.12	0.1	0.1	0.12
Sambreiro Rch	5935.431	0.26	0.27	0.3	0.26	0.29	0.3	0.29	0.29	0.3	0.29
Sambreiro Rch	5450.645	0.37	0.38	0.41	0.36	0.4	0.4	0.42	0.4	0.4	0.42
Sambreiro Rch	4415.756	0.83	0.79	0.8	0.79	0.71	0.69	0.67	0.7	0.68	0.67
Sambreiro Rch	3227.193	0.3	0.28	0.32	0.28	0.29	0.29	0.31	0.28	0.29	0.31
Sambreiro Rch	2595.2	0.57	0.48	0.49	0.5	0.42	0.41	0.39	0.42	0.41	0.39
S.Eleme Rch	15231.35	0.03	0.03	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04
S.Eleme Rch	14635.09	0.15	0.15	0.15	0.14	0.13	0.12	0.12	0.13	0.12	0.12
S.Eleme Rch	13041.89	0.63	0.52	0.45	0.57	0.36	0.34	0.31	0.36	0.33	0.31
S.Eleme Rch	11716.79	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02
S.Eleme Rch	10548.3	0.35	0.31	0.28	0.32	0.21	0.19	0.16	0.2	0.18	0.16
S.Eleme Rch	9228.045	0.13	0.12	0.13	0.12	0.12	0.12	0.13	0.12	0.12	0.13
S.Eleme Rch	8835.141	0.51	0.42	0.37	0.45	0.29	0.27	0.25	0.29	0.27	0.25
S.Eleme Rch	7651.621	0.04	0.04	0.05	0.04	0.04	0.04	0.05	0.04	0.04	0.05
S.Eleme Rch	6509.708	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
S.Eleme Rch	5793.06	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
S.Eleme Rch	4682.95	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
S.Eleme Rch	3806.595	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
S.Eleme Rch	3467.46	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
S.Eleme Rch	3018.646	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
S.Eleme Rch	2648.755	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02
S.Eleme Rch	2288.26	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
S.Eleme Rch	2050.328	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Rumumasi Reach	5357.174	0.18	0.22	0.28	0.2	0.33	0.35	0.38	0.33	0.35	0.38
Rumumasi Reach	4997.979	0.08	0.1	0.14	0.09	0.17	0.2	0.24	0.17	0.2	0.24
Rumumasi Reach	4579.672	0.04	0.05	0.07	0.04	0.09	0.1	0.14	0.09	0.11	0.14
Rumumasi Reach	3195.744	1.67	1.79	1.99	1.73	2.13	2.21	1.32	2.12	2.22	1.32
Rumumasi Reach	2923.519	0.03	0.04	0.06	0.04	0.08	0.08	0.11	0.08	0.08	0.11
Rumumasi Reach	2584.753	0.23	0.25	0.27	0.24	0.28	0.28	0.26	0.28	0.28	0.26
Rumumasi Reach	2217.213	1.94	2.01	2.19	1.98	2.24	1.62	1.12	2.27	1.61	1.12
Rumumasi Reach	1878.588	0.4	0.43	0.48	0.42	0.52	0.54	0.55	0.52	0.54	0.55
Rumumasi Reach	1630.329	0.43	0.46	0.48	0.46	0.49	0.48	0.48	0.49	0.48	0.48
Rumumasi Reach	778.4335	0.47	0.5	0.55	0.5	0.58	0.6	0.59	0.58	0.59	0.59
Rumumasi Reach	473.6282	1.01	1.01	1.09	1.08	1.12	1.1	0.81	1.12	1.09	0.81
PhC Trib Rch	4665.434	0.05	0.05	0.06	0.05	0.06	0.06	0.07	0.06	0.06	0.07
PhC Trib Rch	4482.177	0.05	0.05	0.06	0.05	0.06	0.06	0.07	0.06	0.06	0.07
PhC Trib Rch	4233.093	0.05	0.05	0.06	0.05	0.06	0.06	0.07	0.06	0.06	0.07
PhC Trib Rch	3941.49	0.07	0.07	0.09	0.07	0.08	0.09	0.1	0.08	0.09	0.1
PhC Trib Rch2	2557.172	0.34	0.36	0.37	0.33	0.33	0.33	0.34	0.32	0.33	0.34
PhC Trib Rch2	2219.451	0.3	0.31	0.32	0.28	0.28	0.28	0.29	0.27	0.28	0.29
PhC Trib Rch2	1858.75	0.22	0.23	0.24	0.21	0.21	0.21	0.22	0.21	0.21	0.22
PhC Trib Rch2	1203.888	0.25	0.27	0.29	0.24	0.25	0.25	0.27	0.25	0.25	0.27
PhC River 3 Rch	3911.49	0.07	0.09	0.1	0.08	0.12	0.12	0.14	0.12	0.12	0.14
PhC River 3 Rch	3500.946	0.08	0.1	0.11	0.09	0.12	0.13	0.15	0.12	0.13	0.15

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
PhC River 3 Rch	3118.827	0.07	0.08	0.09	0.08	0.11	0.11	0.12	0.11	0.11	0.12
PhC River 3 Rch	2647.605	0.06	0.07	0.08	0.07	0.1	0.1	0.11	0.1	0.1	0.11
PhC Rv3 Rch	1318.699	0.12	0.14	0.16	0.13	0.19	0.19	0.22	0.19	0.19	0.22
PhC Rv3 Rch	1104.487	0.12	0.14	0.16	0.13	0.19	0.2	0.21	0.19	0.2	0.21
PhC Rv3 Rch	794.874	0.12	0.13	0.15	0.12	0.17	0.18	0.2	0.17	0.18	0.2
PhC River 2 Rch	5693.304	0.11	0.12	0.15	0.12	0.17	0.18	0.2	0.17	0.18	0.2
PhC River 2 Rch	5257.414	0.11	0.13	0.15	0.12	0.18	0.19	0.22	0.18	0.19	0.22
PhC River 2 Rch	4436.802	0.11	0.12	0.14	0.12	0.16	0.16	0.18	0.16	0.16	0.18
PhC River 2 Rch	3818.894	0.12	0.14	0.17	0.13	0.2	0.21	0.23	0.2	0.21	0.23
PhC River 2 Rch	3163.156	0.08	0.09	0.11	0.09	0.12	0.12	0.13	0.12	0.12	0.13
PhC River 2 Rch	2565.354	0.05	0.06	0.07	0.05	0.08	0.09	0.09	0.08	0.08	0.09
PhC River 2 Rch	2017.433	0.09	0.1	0.11	0.09	0.12	0.12	0.13	0.12	0.12	0.13
PhC River 1 Rch	10846.61	0.2	0.25	0.32	0.23	0.39	0.41	0.46	0.39	0.41	0.46
PhC River 1 Rch	10244.22	0.15	0.17	0.22	0.17	0.27	0.28	0.33	0.27	0.28	0.33
PhC River 1 Rch	9710.716	0.19	0.22	0.29	0.21	0.36	0.38	0.44	0.36	0.38	0.44
PhC River 1 Rch	8587.027	0.08	0.09	0.12	0.09	0.16	0.17	0.2	0.16	0.17	0.2
PhC River 1 Rch	7690.577	0.05	0.06	0.07	0.05	0.09	0.1	0.11	0.09	0.1	0.11
PhC River 1 Rch	7306.689	0.04	0.04	0.06	0.04	0.07	0.08	0.1	0.07	0.08	0.1
PhC River 1 Rch	6776.999	0.07	0.09	0.11	0.08	0.14	0.14	0.16	0.14	0.14	0.16
PhC River 1 Rch	6264.194	0.08	0.09	0.12	0.09	0.15	0.16	0.18	0.15	0.16	0.18
PhC River 1 Rch	5899.262	0.06	0.08	0.1	0.07	0.13	0.13	0.15	0.13	0.13	0.15
PhC River 1 Rch	5461.963	0.04	0.05	0.07	0.05	0.09	0.1	0.11	0.09	0.1	0.11
PhC River 1 Rch	4882.684	0.3	0.36	0.46	0.34	0.58	0.61	0.67	0.58	0.61	0.67
PhC River 1 Rch	4447.399	0.31	0.38	0.49	0.35	0.63	0.66	0.77	0.62	0.66	0.77
PhC Rv1 rch2	1914.555	0.11	0.12	0.16	0.12	0.19	0.2	0.23	0.19	0.2	0.23
PhC Rv1 rch2	1414.925	0.09	0.11	0.14	0.1	0.17	0.18	0.21	0.17	0.18	0.21
PhC Rv1 rch2	1070.069	0.09	0.1	0.13	0.1	0.16	0.17	0.2	0.16	0.17	0.2

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
PhC Rv1 rch2	728.6349	0.08	0.09	0.12	0.09	0.15	0.16	0.18	0.15	0.16	0.18
Okrika Rch	13665.25	0.47	0.46	0.44	0.47	0.37	0.37	0.34	0.38	0.37	0.34
Okrika Rch	12794.63	0.09	0.08	0.12	0.09	0.07	0.08	0.1	0.07	0.08	0.1
Okrika Rch	12072.56	0.13	0.12	0.15	0.13	0.1	0.11	0.12	0.1	0.11	0.12
Okrika Rch	11764	0.04	0.04	0.06	0.04	0.03	0.04	0.05	0.03	0.04	0.05
Okrika Rch	11324.64	0.23	0.22	0.23	0.23	0.18	0.18	0.18	0.18	0.18	0.18
Okrika Rch	10998.09	0.05	0.04	0.06	0.05	0.04	0.04	0.05	0.04	0.04	0.05
Okrika Rch	10578.72	1.65	1.6	1.81	1.68	1.26	1.29	1.41	1.27	1.31	1.41
Okrika Rch	10243.39	0.2	0.19	0.26	0.21	0.16	0.17	0.22	0.16	0.17	0.22
Okrika Rch	9061.025	0.81	0.78	0.88	0.82	0.61	0.62	0.66	0.61	0.63	0.66
Okrika Rch	8374.236	0.25	0.23	0.31	0.26	0.18	0.19	0.23	0.18	0.19	0.23
Okrika Rch	7687.396	0.88	0.83	0.88	0.89	0.53	0.53	0.54	0.54	0.53	0.54
Okrika Rch	7072.159	0.18	0.16	0.23	0.18	0.12	0.13	0.17	0.12	0.13	0.17
Okrika Rch	6655.038	0.44	0.41	0.53	0.45	0.28	0.3	0.37	0.29	0.31	0.37
Okrika Rch	5649.987	0.17	0.16	0.22	0.18	0.11	0.12	0.16	0.11	0.13	0.16
Okrika Rch	5163.031	1.23	1.13	1.25	1.24	0.66	0.67	0.67	0.67	0.68	0.67
Okrika Rch	4237.385	0.19	0.17	0.23	0.2	0.11	0.12	0.14	0.12	0.12	0.14
Okrika Rch	3678.697	1.49	1.32	1.5	1.5	0.69	0.69	0.74	0.7	0.7	0.74
Okrika Rch	3059.927	0.52	0.4	0.57	0.53	0.23	0.25	0.31	0.23	0.25	0.31
Okrika Rch	2781.317	0.31	0.23	0.34	0.31	0.14	0.15	0.19	0.14	0.15	0.19
Okrika Rch	2379.053	0.21	0.16	0.23	0.21	0.09	0.1	0.13	0.09	0.1	0.13
Okrika Rch	2095.073	0.14	0.11	0.16	0.14	0.06	0.07	0.09	0.06	0.07	0.09
Odual Tributary	2003.022										
Odual Tributary	1487.593	0.05	0.07	0.08	0.05	0.08	0.09	0.11	0.08	0.09	0.11
Odual Tributary	909.9347	0.07	0.08	0.1	0.07	0.1	0.11	0.14	0.1	0.11	0.14
N.Eleme Rch	3551.777	0.32	0.37	0.49	0.33	0.59	0.64	0.77	0.6	0.64	0.77
N.Eleme Rch	3102.823	0.58	0.57	0.67	0.52	0.74	0.77	0.87	0.74	0.77	0.87

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
N.Eleme Rch	2605.724	1.95	2.15	2.4	2.04	2.58	2.65	2.86	2.59	2.66	2.86
N.Eleme Rch	1887.28	0.71	0.73	0.7	0.74	0.66	0.64	0.57	0.66	0.64	0.57
N.Eleme Rch	1361.515	0.12	0.14	0.15	0.13	0.16	0.17	0.18	0.16	0.17	0.18
N.Eleme Rch	1063.356	0.15	0.17	0.18	0.17	0.19	0.2	0.21	0.19	0.2	0.21
N.Eleme Rch	624.9445	0.3	0.34	0.31	0.33	0.3	0.29	0.28	0.3	0.29	0.28
Lwr Choba Rch	3117.347	0.15	0.18	0.22	0.16	0.25	0.27	0.33	0.25	0.27	0.33
Lwr Choba Rch	2630.421	0.18	0.22	0.27	0.19	0.3	0.32	0.39	0.3	0.32	0.39
Lwr Choba Rch	2210.917	0.21	0.25	0.31	0.22	0.35	0.38	0.46	0.35	0.38	0.47
Lwr Choba Rch	1505.881	0.1	0.12	0.15	0.11	0.17	0.18	0.22	0.17	0.18	0.22
Lwr Choba Rch	1177.626	0.13	0.15	0.18	0.13	0.21	0.22	0.27	0.21	0.22	0.27
Lwr Choba Rch	716.0721	0.94	0.99	1.17	0.93	1.25	1.3	1.47	1.25	1.3	1.47
Lw Eagle Isl Rch	4028.788	0.06	0.07	0.08	0.06	0.06	0.05	0.05	0.06	0.05	0.05
Lw Eagle Isl Rch	3553.737	0.16	0.16	0.16	0.15	0.13	0.13	0.12	0.13	0.13	0.12
Lw Eagle Isl Rch	2981.277	0.08	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.06	0.06
Lw Eagle Isl Rch	2431.181	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Lw Eagle Isl Rch	1818.94	0.14	0.12	0.11	0.13	0.08	0.07	0.06	0.08	0.07	0.06
Lw Eagle Isl Rch	1129.461	0.19	0.19	0.18	0.17	0.14	0.13	0.12	0.14	0.13	0.12
Lw Eagle Isl Rch	535.0954	0.52	0.49	0.48	0.47	0.41	0.4	0.38	0.4	0.4	0.38
Kor Rive Rch	4708.004	0.05	0.06	0.08	0.05	0.07	0.07	0.1	0.07	0.08	0.19
Kor Rive Rch	4163.468	0.08	0.09	0.11	0.08	0.1	0.11	0.14	0.11	0.12	0.26
Kor Rive Rch	3440.388	0.1	0.1	0.12	0.09	0.11	0.12	0.14	0.12	0.13	0.22
Kor Rive Rch	2678.573	0.15	0.15	0.17	0.15	0.16	0.17	0.2	0.17	0.18	0.36
Kor Rive Rch	1504.354	0.15	0.16	0.2	0.15	0.18	0.19	0.24	0.19	0.21	0.45
Kor Rive Rch	749.9553	1.87	1.9	2.1	1.85	2	2.08	2.31	2.06	2.14	3.09
Iwofe Rch	2657.526										
Iwofe Rch	2405.32	0.3	0.42	0.44	0.35	0.44	0.44	0.42	0.44	0.44	0.42
Iwofe Rch	1987.4	0.46	0.56	0.61	0.49	0.62	0.65	0.74	0.62	0.65	0.74

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Iwofe Rch	1368.51	0.17	0.22	0.24	0.19	0.24	0.26	0.29	0.24	0.26	0.29
Iwofe Rch	644.0602	0.12	0.16	0.17	0.13	0.18	0.19	0.2	0.18	0.19	0.2
Iwofe Rch	374.4696	0.18	0.24	0.27	0.19	0.28	0.3	0.34	0.28	0.3	0.34
PhC Habour	11720.27										
PhC Habour	11368.09	0.27	0.29	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
PhC Habour	10421.94	0.17	0.21	0.23	0.19	0.23	0.23	0.24	0.23	0.23	0.24
PhC Habour	9685.051	0.05	0.07	0.08	0.06	0.08	0.09	0.11	0.08	0.09	0.11
PhC Habour	9272.59	0.05	0.07	0.08	0.05	0.08	0.09	0.11	0.08	0.09	0.11
PhC Habour	8810.765	0.07	0.1	0.11	0.08	0.11	0.12	0.14	0.11	0.12	0.14
Isaka Lower Rch	7499.176	0.42	0.45	0.42	0.43	0.4	0.39	0.36	0.4	0.39	0.36
Isaka Lower Rch	7137.471	0.49	0.56	0.57	0.52	0.56	0.56	0.58	0.56	0.56	0.58
Isaka Lower Rch	6491.283	0.14	0.17	0.16	0.15	0.16	0.15	0.15	0.16	0.15	0.15
Isaka Lower Rch	5762	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Isaka Lower Rch	5223.925	0.05	0.06	0.06	0.05	0.06	0.07	0.07	0.06	0.07	0.07
Isaka Lower Rch	4238.011	0.07	0.08	0.09	0.07	0.09	0.09	0.11	0.09	0.09	0.11
Isaka Lower Rch	3629.504	0.61	0.7	0.68	0.66	0.65	0.65	0.63	0.65	0.65	0.63
Isaka Lower Rch	2256.603	0.17	0.22	0.24	0.19	0.24	0.25	0.29	0.24	0.25	0.29
Isaka Lower Rch	1248.921	0.18	0.24	0.26	0.2	0.26	0.28	0.32	0.26	0.28	0.32
Elelenwo Reach	2859.101	0.25	0.29	0.36	0.26	0.38	0.39	0.42	0.38	0.39	0.42
Elelenwo Reach	2569.424	0.16	0.2	0.28	0.17	0.34	0.35	0.38	0.34	0.35	0.38
Elelenwo Reach	2247.295	0.51	0.62	0.8	0.55	0.88	0.9	0.94	0.88	0.9	0.94
Elelenwo Reach	1641.735	1.49	1.09	0.63	1.56	0.57	0.55	0.54	0.57	0.55	0.54
Elelenwo Reach	1239.382	0.11	0.13	0.16	0.12	0.19	0.2	0.24	0.19	0.2	0.24
Elelenwo Reach	925.7126	0.23	0.22	0.23	0.22	0.24	0.25	0.28	0.24	0.25	0.28
Egbema Upper Rch	7620.897	0.26	0.16	0.25	0.16	0.16	0.2	0.3	0.16	0.19	0.3
Egbema Upper Rch	6975.507	0.23	0.14	0.22	0.14	0.14	0.17	0.25	0.13	0.16	0.25
Egbema Upper Rch	6615.183	0.25	0.16	0.24	0.16	0.15	0.18	0.28	0.15	0.18	0.27

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Egbema Upper Rch	6056.989	0.29	0.19	0.27	0.2	0.18	0.21	0.29	0.17	0.21	0.29
Egbema Upper Rch	5797.456	0.3	0.19	0.27	0.2	0.18	0.21	0.3	0.18	0.21	0.3
Egbema Upper Rch	5091.818	0.57	0.36	0.49	0.4	0.34	0.38	0.5	0.33	0.38	0.49
Egbema Upper Rch	4798.4	0.3	0.19	0.28	0.2	0.18	0.21	0.31	0.17	0.21	0.31
Egbema Upper Rch	4247.958	0.69	0.43	0.61	0.48	0.4	0.46	0.61	0.39	0.45	0.6
Egbema Upper Rch	3888.238	0.6	0.34	0.53	0.37	0.33	0.39	0.57	0.32	0.38	0.57
Egbema Lower Rch	3066.631	0.2	0.29	0.31	0.21	0.31	0.34	0.41	0.31	0.34	0.41
Egbema Lower Rch	2515.038	0.22	0.27	0.28	0.22	0.28	0.29	0.32	0.28	0.29	0.32
Egbema Lower Rch	2087.512	0.24	0.26	0.26	0.24	0.25	0.24	0.2	0.26	0.24	0.2
Egbema Lower Rch	1587.756	0.16	0.2	0.21	0.16	0.2	0.21	0.22	0.21	0.21	0.22
Egbema Lower Rch	1011.06							0.01			0.01
Egbema Lower Rch	600.1398										
Egbema Lower Rch	219.8786										
Eagle Isl Rch	20175.23	0.2	0.22	0.26	0.2	0.26	0.27	0.31	0.26	0.27	0.31
Eagle Isl Rch	19541.11	0.13	0.15	0.17	0.13	0.17	0.18	0.2	0.17	0.18	0.2
Eagle Isl Rch	18815.8	0.15	0.16	0.18	0.14	0.18	0.18	0.21	0.18	0.18	0.21
Eagle Isl Rch	18228.53	0.13	0.14	0.16	0.13	0.16	0.17	0.19	0.16	0.17	0.19
Eagle Isl Rch	17633.08	0.09	0.1	0.1	0.09	0.1	0.1	0.1	0.1	0.1	0.1
Eagle Isl Rch	17011.49	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Eagle Isl Rch	15623.3	0.06	0.06	0.06	0.05	0.06	0.06	0.05	0.06	0.06	0.05
Eagle Isl Rch	15122.23	0.56	0.55	0.54	0.55	0.51	0.49	0.43	0.51	0.49	0.43
Eagle Isl Rch	14395.02	0.25	0.28	0.32	0.25	0.31	0.33	0.36	0.31	0.33	0.36
Eagle Isl Rch	13377.85	0.41	0.45	0.51	0.41	0.5	0.52	0.59	0.5	0.52	0.59
Eagle Isl Rch	12545	0.33	0.35	0.39	0.33	0.38	0.4	0.43	0.38	0.4	0.43
Eagle Isl Rch	11194.69	0.59	0.64	0.71	0.58	0.68	0.71	0.79	0.68	0.71	0.79
Eagle Isl Rch	10397.37	0.24	0.26	0.28	0.23	0.27	0.28	0.31	0.27	0.28	0.31
Eagle Isl Rch	9679.32	0.32	0.34	0.38	0.31	0.36	0.37	0.39	0.36	0.37	0.39

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Eagle Isl Rch	9296.871	0.22	0.24	0.27	0.21	0.26	0.27	0.31	0.26	0.27	0.31
Eagle Isl Rch	8156.481	0.46	0.5	0.55	0.45	0.52	0.54	0.6	0.52	0.54	0.6
Eagle Isl Rch	7004.388	0.4	0.43	0.48	0.39	0.45	0.47	0.52	0.45	0.47	0.52
Eagle Isl Rch	6301.9	0.17	0.17	0.19	0.16	0.17	0.16	0.17	0.17	0.16	0.17
Eagle Isl Rch	5171.876	0.3	0.32	0.34	0.29	0.3	0.31	0.32	0.3	0.31	0.32
Eagle Isl Rch	3607.002	0.15	0.16	0.17	0.15	0.15	0.16	0.18	0.15	0.16	0.18
Eagle Isl Rch	2524.504	0.19	0.2	0.21	0.18	0.19	0.19	0.19	0.19	0.19	0.19
Eagle Isl Rch	1789.479	0.27	0.28	0.3	0.25	0.26	0.27	0.26	0.26	0.26	0.26
Eagle Isl Rch	612.6847	0.13	0.14	0.14	0.12	0.13	0.13	0.13	0.13	0.13	0.13
Dutch Isl Rch	3217.171	0.11	0.11	0.13	0.11	0.13	0.14	0.14	0.13	0.14	0.14
Dutch Isl Rch	2847.968	0.07	0.07	0.09	0.07	0.09	0.09	0.1	0.09	0.09	0.1
Dutch Isl Rch	2638.333	0.1	0.1	0.12	0.1	0.12	0.13	0.14	0.12	0.13	0.14
Dutch Isl Rch	2284.159	0.22	0.23	0.26	0.21	0.27	0.28	0.3	0.27	0.28	0.3
Dutch Isl Rch	1930.845	0.12	0.12	0.13	0.11	0.13	0.14	0.13	0.13	0.14	0.13
Dutch Isl Rch	1520.077	0.08	0.08	0.09	0.08	0.09	0.1	0.1	0.09	0.1	0.1
Dutch Isl Rch	1231.084	0.13	0.14	0.15	0.13	0.16	0.16	0.16	0.16	0.16	0.16
Dutch Isl Rch	923.5763	0.58	0.61	0.68	0.58	0.7	0.72	0.7	0.7	0.72	0.7
Degema Upper Rch	10015.86	0.39	0.25	0.34	0.25	0.21	0.25	0.38	0.21	0.25	0.37
Degema Upper Rch	9447.894	0.67	0.4	0.5	0.41	0.31	0.37	0.56	0.3	0.36	0.55
Degema Upper Rch	8176.194	0.32	0.19	0.28	0.18	0.16	0.2	0.32	0.16	0.2	0.32
Degema Upper Rch	7296.695	0.19	0.11	0.15	0.11	0.09	0.11	0.16	0.09	0.1	0.16
Degema Upper Rch	7110.268	0.18	0.1	0.15	0.1	0.09	0.11	0.17	0.09	0.11	0.17
Degema Upper Rch	5995.249	0.11	0.06	0.09	0.06	0.05	0.07	0.11	0.05	0.07	0.1
Degema Lower Rch	3056.964	0.28	0.31	0.38	0.29	0.33	0.36	0.45	0.33	0.36	0.44
Degema Lower Rch	1958.294	0.28	0.31	0.38	0.29	0.34	0.37	0.45	0.33	0.37	0.45
Degema Lower Rch	1459.966	0.35	0.39	0.48	0.37	0.42	0.46	0.54	0.41	0.46	0.54
Degema Lower Rch	655.1443	0.35	0.38	0.44	0.36	0.4	0.42	0.5	0.39	0.42	0.5

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Choba Rch	12556.62	0.08	0.09	0.1	0.08	0.11	0.12	0.14	0.11	0.12	0.14
Choba Rch	11981.62	0.08	0.09	0.1	0.08	0.11	0.12	0.14	0.11	0.12	0.14
Choba Rch	11356.44	0.08	0.09	0.11	0.08	0.12	0.14	0.17	0.12	0.14	0.17
Choba Rch	10501.81	0.17	0.19	0.19	0.17	0.19	0.19	0.17	0.19	0.19	0.17
Choba Rch	9117.822	0.16	0.2	0.25	0.17	0.27	0.3	0.34	0.27	0.3	0.34
Choba Rch	7221.321	0.06	0.07	0.07	0.06	0.09	0.09	0.08	0.09	0.09	0.09
Choba Rch	6630.73	0.11	0.14	0.14	0.12	0.18	0.19	0.18	0.18	0.19	0.2
Choba Rch	5315.833	0.14	0.18	0.11	0.15	0.15	0.14	0.13	0.16	0.14	0.14
Choba Rch	3529.868	0.09	0.12	0.11	0.09	0.15	0.15	0.15	0.15	0.15	0.16
Choba Rch	2739.644	0.05	0.07	0.06	0.05	0.09	0.09	0.1	0.09	0.09	0.11
Choba Rch	1148.281	0.02	0.03	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05
Choba Rch	589.6992	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Buguma Rch	22169.42	0.01	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.02	0.03
Buguma Rch	20077.09	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.03
Buguma Rch	19287.01	0.02	0.02	0.03	0.02	0.03	0.03	0.04	0.03	0.03	0.04
Buguma Rch	14320.91	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Buguma Rch	13044.47	0.06	0.06	0.07	0.06	0.07	0.07	0.08	0.07	0.07	0.08
Buguma Rch	11091.03	0.1	0.1	0.09	0.1	0.09	0.09	0.1	0.09	0.09	0.1
Buguma Rch	8542.064	0.13	0.15	0.13	0.13	0.13	0.14	0.16	0.13	0.14	0.16
Buguma Rch	6771.962	0.14	0.15	0.17	0.14	0.18	0.19	0.22	0.18	0.19	0.22
Buguma Rch	5756.395	0.34	0.35	0.35	0.34	0.35	0.36	0.37	0.35	0.36	0.37
Buguma Rch	4494.115	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Buguma Rch	3652.478	0.19	0.21	0.25	0.19	0.26	0.27	0.31	0.25	0.27	0.31
Buguma Rch	2207.349	0.39	0.43	0.51	0.39	0.52	0.54	0.57	0.51	0.54	0.57
Buguma Rch	1463.724	0.3	0.33	0.39	0.3	0.4	0.42	0.48	0.4	0.42	0.48
Buguma Rch	293.3568	0.34	0.37	0.43	0.34	0.44	0.46	0.52	0.44	0.46	0.52
Bori River Rch	11178.96	0.04	0.05	0.06	0.04	0.06	0.07	0.09	0.06	0.07	0.09

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Bori River Rch	7423.903	0.02	0.03	0.04	0.02	0.03	0.04	0.05	0.03	0.04	0.05
Bori River Rch	5467.596	0.06	0.07	0.09	0.06	0.09	0.09	0.12	0.09	0.09	0.11
Bori River Rch	4403.423	0.1	0.11	0.14	0.1	0.14	0.15	0.18	0.13	0.15	0.18
Bori River Rch	2524.635	0.13	0.14	0.16	0.13	0.16	0.16	0.18	0.15	0.16	0.18
Bori River Rch	1561.587	0.21	0.23	0.27	0.21	0.26	0.28	0.32	0.26	0.28	0.31
Bori River Rch	543.6863	2.72	2.83	3.07	2.72	3.05	3.17	3.4	3.04	3.15	3.38
Bonny River Rch	16321.99	0.1	0.12	0.14	0.11	0.15	0.16	0.19	0.15	0.16	0.19
Bonny River Rch	15959.9	0.1	0.12	0.13	0.11	0.15	0.16	0.18	0.15	0.16	0.18
Bonny River Rch	15252.99	0.1	0.11	0.13	0.1	0.13	0.14	0.16	0.13	0.14	0.16
Bonny River Rch	14245.93	0.09	0.1	0.11	0.09	0.12	0.12	0.14	0.12	0.12	0.14
Bonny River Rch	13232.1	0.08	0.09	0.11	0.09	0.11	0.12	0.13	0.11	0.12	0.13
Bonny River Rch	12346.08	0.08	0.09	0.1	0.08	0.1	0.11	0.12	0.1	0.11	0.12
Bonny River Rch	11616.86	0.08	0.09	0.1	0.08	0.1	0.1	0.12	0.1	0.11	0.12
Bonny River Rch	11070.12	0.07	0.08	0.09	0.08	0.1	0.1	0.11	0.1	0.1	0.11
Bonny River Rch	10425.34	0.05	0.06	0.06	0.05	0.07	0.07	0.08	0.07	0.07	0.08
Bonny River Rch	9196.691	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.05	0.05	0.06
Bonny River Rch	7985.233	0.03	0.03	0.04	0.03	0.04	0.04	0.05	0.04	0.04	0.05
Bonny River Rch	6473.635	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.04	0.04	0.05
Bonny River Rch	5316.221	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.03	0.04	0.04
Bonny River Rch	4022.241	0.03	0.03	0.04	0.03	0.04	0.04	0.05	0.04	0.04	0.05
Bonny River Rch	2471.691	0.04	0.05	0.05	0.04	0.05	0.06	0.06	0.05	0.06	0.06
Bonny River Rch	1268.273	0.06	0.07	0.08	0.06	0.08	0.09	0.1	0.08	0.09	0.1
Bonny River Rch	314.701	0.08	0.09	0.1	0.08	0.1	0.11	0.12	0.1	0.11	0.12
Abua Rch	5049.264	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Abua Rch	4412.543	0.03	0.03	0.05	0.04	0.04	0.05	0.05	0.04	0.05	0.05
Abua Rch	3617.452	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Abua Rch	2596.925	0	0	0	0	0	0	0.01	0	0	0.01

Reach	River Sta	1986 (U1)	1995	2003	U2	UMP44yr	UMP57yr	UMP100yr	UUMP44yr	UUMP57yr	UUMP100yr
Abua Rch	1425.898	0.03	0.03	0.05	0.04	0.04	0.05	0.06	0.04	0.05	0.06
Abua Rch	887.2714	0.02	0.03	0.04	0.03	0.03	0.04	0.05	0.03	0.04	0.05

Appendix 7.5 Interpretation of flood zones under three probabilities. Zone 1 is the Low probability zone, Zone 2 is the medium probability zone, while Zone 3 is the high probability.

Flood Zone	Definition	Note
Zone 1- Low Probability	Potential flooding on land due to storm of 1 in 100yr annual probability.	The chance of flooding in any year is 1% (1 in 100)
Zone 2 -Medium Probability	Potential flooding on land due to storm of 1 in 38yr annual probability.	Based on 2003 event. In this case, the chance of flooding in any year is 2.6% (1 in 38).
Zone 3 -High Probability	Potential flooding on land due to storm of 1 in 2.5yr annual probability.	Based on the 1986 storm event. In this case, the chance of flooding in any year is than 40% (1 in 2.5)

Appendix 7.6 Number of buildings under different hazard ratings in the areas analysed (in Figures 41-47). The table shows about 248 builds in the areas analysed are subject to floods with very high damage potential.

	Number of Buildings				
Area	Very High	High	Medium	Low	Total
Old industrial layout	21	45	94	220	380
Borokiri	22	243	303	436	1004
Abo Ama area	74	194		32	300
Eastern bypass	82		26	22	130
Wiyikara	42	30	0	17	89
Eagle Island	2	56	71	63	192
Onne	5	9	3	11	28
	248	577	497	801	2123